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Demonstration of Decision Support Tools for Evaluating Ground Combat System Survivability, Lethality, and Mobility at the Tactical, Operational, and Strategic Levels of War

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Demonstration of Decision Support Tools for Evaluating Ground Combat System Survivability, Lethality, and Mobility at the Tactical, Operational, and Strategic Levels of War

by

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Dedication

To the Keena family: my wife Patricia; my children Gianna and Joshua… with love

Joshua M. Keena

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Demonstration of Decision Support Tools for Evaluating Ground Combat System Survivability, Lethality, and Mobility at the Tactical, Operational, and Strategic Levels of War

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Decision makers often present military researchers with a most daunting challenge: to pursue, with some level of prophetic certainty, innovative concepts that will yield increased capabilities during future wars against forecasted threats in not-yet-determined locations. This conundrum is complicated further with the requirement that the proposed technology yield benefit throughout the various strata of military operations. In the maturation of an advanced capability enabled by a technological advancement, a groundbreaking design should simultaneously demonstrate performance overmatch against an envisioned foe while showing that the costs associated with development, procurement, and operation outweigh reverting to an incremental advancement in the conventional means of delivering combat power.

This manuscript focuses on the construction and utilization of decision support tools for use by scientists and engineers charged with providing a quantitative evaluation of an advanced ground combat system. The concepts presented focus on the effects and synergy regarding the combat vehicle principal attributes of survivability, lethality, and mobility. Additionally, this study provides a framework for analysis of these attributes when screened at the tactical, operational, and strategic levels of war. These concepts are presented and demonstrated from both the candidate selection (or choice) perspective, and the concept development (or design) perspective. As an example of this approach, this study includes a comparison of conventional powder gun cannonry versus a specific type of electromagnetic launch device known as the railgun.

The decision support tools formulated in this dissertation allow the user to distill, at a coarse level of fidelity, the parametric relationships between system survivability, lethality, and mobility for advanced weapon system concepts. The proposed methods are suited for evaluation at the nascent stages of development, when the information normally applied in standard methods is sparse. This general approach may also be valuable in contemporary acquisition strategies employed in urgent fielding efforts, where the immediacy of the problem can benefit from an expedient and efficient method of analyzing the coupled and synergistic effects of implementing a proposed technology. While advantage is typically measured in terms of performance overmatch at the platform level, the broadening of this consideration vertically to higher levels of military command can aid in identifying the competing issues and complementary relationships related to a technical approach. Finally, given the backdrop demonstration for the framework, this manuscript may serve as a brief summary of system fundamentals and design theory for direct fire powder gun cannonry and electromagnetic railguns.

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4GW	fourth generation warfare
AAR	after-action review, report
AHP	analytic hierarchy process
AIAA	American Institute of Aeronautics and Astronautics
AMC	U.S. Army Materiel Command
ANOVA	analysis of variance
APC	armored personnel carrier
BDA	battle damage assessment
BRAC	base realignment and closure
C-IED	counter-improvised explosive device
COE	contemporary operating environment
COIN	counterinsurgency operations
CSI	combat survivability index
DoD	U.S. Department of Defense
DOE	design of experiments
DTIC	U.S. Defense Technical Information Center
EML	electromagnetic launch
FANG	Fast Adaptable Next Generation vehicle
FM	U.S. Army Field Manual
FCS	Future Combat System
GCS	ground combat systems
GCV	Ground Combat Vehicle (with reference to U.S. Army program)
HMMWV	high mobility multiwheel vehicle

HOQ	house of quality
IAT	Institute for Advanced Technology
IED	improvised explosive device
IFV	infantry fighting vehicle
IQC	Intermediate Qualification Course
IRB	Institutional Review Board
JIEDDO	Joint IED Defeat Organization
JRATS	Joint Reconnaissance and Targeting System
LCM	life-cycle management
LRIP	low rate initial production
MADM	multiattribute decision making
MCDM	multicriteria decision making
MCO	major combat operations
MODM	multiobjective decision making
MRAP	mine resistant ambush protected vehicle
OCO	overseas contingency operations
OEF	Operation Enduring Freedom
OFAT	one factor at a time
OIF	Operation Iraqi Freedom
ORS	Office of Research Support
QFD	quality function deployment
TTP	tactics, techniques, and procedures
UAV	unmanned aerial vehicle
XTV	experimental tracked vehicle
XWV	experimental wheeled vehicle

Chapter 1: Introduction

No good decision was ever made in a swivel chair.
—*General George S. Patton Jr.*

There are over two thousand years of experience to tell us that the only thing harder than getting a new idea into the military mind is to get the old one out.
—*Basil H. Liddell Hart*

1.1 Overview

For nearly a century, the U.S. Army, with well-defined peer threats and a focus on major combat operations, has steadily pursued ground combat vehicles designed to afford future mounted warriors with advanced levels of survivability, lethality, and mobility. However, the contemporary transformation in warfare, coupled with the increasing rate of change in functional requirements, has challenged fighting platform design and selection processes previously built for the Cold War environment. This chapter presents relevant observations regarding ground combat vehicle design successes as well as opportunities for improvement. Based largely on the opportunities for improvement identified from the last decade, a hypothesis and set of research questions was developed, the answers to which are aimed at improving future ground combat vehicle design and selection efforts. In order to contribute to an improvement in the field of fighting vehicle advancement, a literature review was conducted on both decision analysis and ground combat vehicle design theory. This review yielded insight as to how decision support tools might best be constructed in order to facilitate future efforts involving the future pursuit of advanced ground combat vehicles.

1.2 Background

Behind the development or adoption of any revolutionary military technology resides a moment when, in a challenging and contentious environment, a decision is made to pursue a novel concept to fruition. Historical examples include incorporating steam power over sail for naval ships, mounting ground forces on vehicles driven by internal combustion engines instead of riding horses and mules, and harnessing gas turbine power plants in place of piston engines and spinning propellers on fixed-wing military aircraft (Figure 1). While there was an eventual positive outcome for each of these pursuits, contemporary accounts of nearly every example of military technology development or adoption illustrate that considerable time was spent deliberating about, entrenching against, and even overtly delaying the implementation of a disruptive technology.[1] In hindsight, the prescience and courage associated with the decision to mature these revolutionary, disruptive technologies might seem trivial, but at the time, these were controversial topics fraught with significant monetary risk, large uncertainty about system performance, and, perhaps most saliently, real threat to human life.

[1] Peter W. Singer, "How the U.S. Military Can Win The Robotic Revolution" *Popular Mechanics* (May 2010) 36-39. He is Senior Fellow Director of the 21st Century Defense Initiative at the Brookings Institution. Singer is widely considered one of the world's leading experts on 21st century warfare, particularly with respect to military technology.

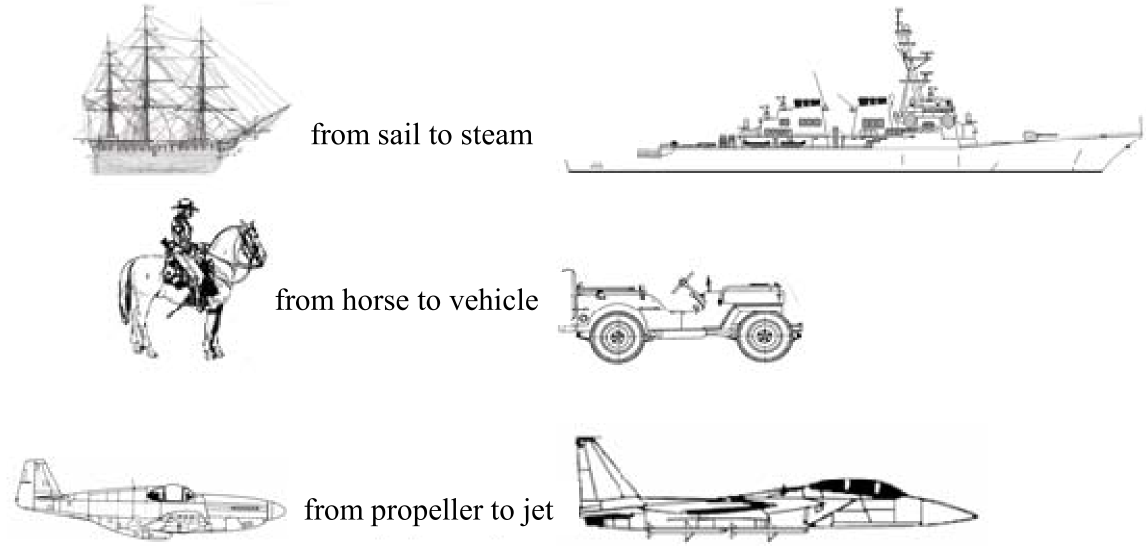

Figure 1: Historical examples of transitioned revolutionary U.S. military technologies in projecting sea, land, and air power. Examples on the left are the precursors, and examples on the right are successors several generations after adoption of the disruptive technology. From top left to bottom right, these include the USS Constitution, the Aegis Cruiser, the horse cavalryman, the M38 Willys Jeep, the P-51 Mustang, and the F-15 Strike Eagle.[2]

The decision to develop and field ground combat vehicles falls into the category of revolutionary military technologies. Born from very humble origins and under the incredible duress of World War I, the first ground combat vehicles were essentially armored motorcars and tractors equipped with basic weapons mounted in simple turrets. Even in this rudimentary and primitive form, the earliest fighting vehicles provided crewmembers with the constitutive elements necessary for a ground combat platform, i.e., protection, firepower, and freedom to move. While the functional requirements and

[2] Sources for graphics include the USS Constitution: (www.bestscalemodels.com), Aegis Cruiser: (www.photobucket.com/AegisCruiserEvolution.gif), Horse Cavalryman: (www.virtualhorses.com/graphics/civilwar.htm), M38 Willys Jeep: (www.carblueprints.info/eng/view/willys/willys-jeep-1), P-51 Mustang: (www.shipbucket.com), and the F-15 Strike Eagle: (www.amazingpaperairplanes.com/Eagle_F-15/AboutF-15_Eagle.html).

performance capabilities of modern fighting vehicles far exceed the early examples of mounted combat platforms, combat vehicles, both past and present, all share the possession of an inherent capacity to provide some level of survivability, lethality, and mobility to the crewmembers that ride and fight them in battle.

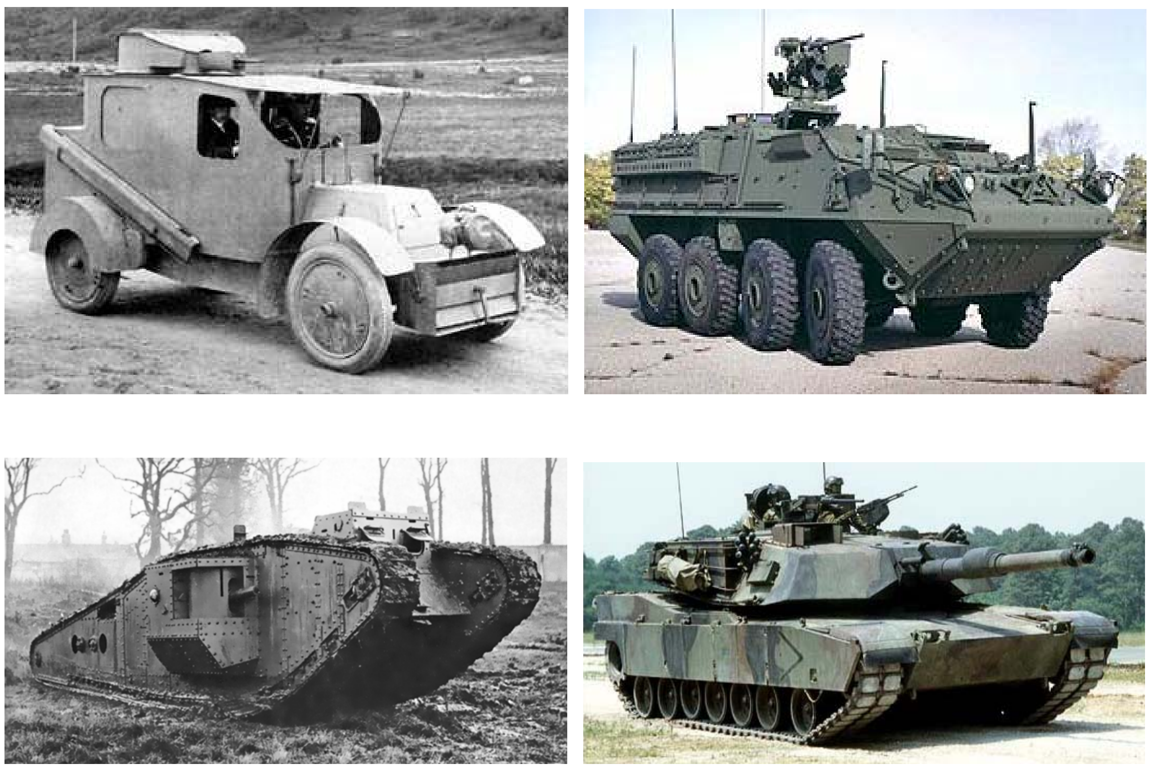

Figure 2: Historical and modern examples of fighting vehicles. The photo in the upper left is one of the first armored cars, the Russian developed and French built Nakashidze-Charon, circa 1912. The photo in the upper right is of the modern U.S. M1126 Stryker fighting vehicle. The photo in the bottom left is one of the first tanks, the British Mark I, circa 1916. The photo in the bottom right is of the modern U.S. M1 Abrams tank.[3]

[3] Sources for photos include the Nakashidze-Charon: (commons.wikimedia.org/wiki/File:Nakashidze-Charon.jpg), the U.S. Stryker: (www.wikipedia.org/wiki/Stryker), the Mark I tank (http://wa8.wikispaces.com/Tank), and the U.S. M1 Abrams tank (www.fprado.com/armorsite/abrams.htm)

Regarding the future of mounted combat and the decisions associated with advancing fighting vehicle performance, the abundance of dilemmas facing current U.S. Department of Defense (DoD) leadership in the Contemporary Operating Environment (COE) is as great today as when those historic decisions were made to field the first ground combat vehicles. The COE is defined as "a composite of the conditions, circumstances, and influences that affect the employment of capabilities and bear on the decisions of the commander."[4] Presently, the COE can be classified as a veritable squall line of competing resources for research and development activities.[5] A list of these burdens includes the continued transformation of military forces from a Cold War, peer-threat focus to the present-day efforts with counter-insurgency (COIN) and stability operations; base realignment and closure (BRAC) proceedings; ongoing overseas contingency operations (OCO) including Operations Iraqi Freedom and Enduring Freedom (OIF and OEF) in Iraq and Afghanistan; and decades of life-cycle management (LCM) involving tens of billions of dollars for fielded systems. To safeguard future forces and sustain global military superiority in the most efficient and effective manner, technologists working in defense-related research are asked to forecast a tall order, namely to predict—with some level of prophetic certainty—which innovative concepts will provide increased capabilities in future conflicts against anticipated threats in unknown locations.[6]

[4] Joint Publication 1-02, *Department of Defense Dictionary of Military and Associated Terms*, 13 June 2007.
[5] David A. Fulghum, "Competing Demands on Defense Budget Produce Desperate Crisis" *Aviation Week and Space Technology* (November 2005) 2-3.
[6] Douglas A. Macgregor, *Breaking the Phalanx: A New Design for Landpower in the 21st Century.* (Newport, Connecticut: Praeger Publishers, 1997) 191.

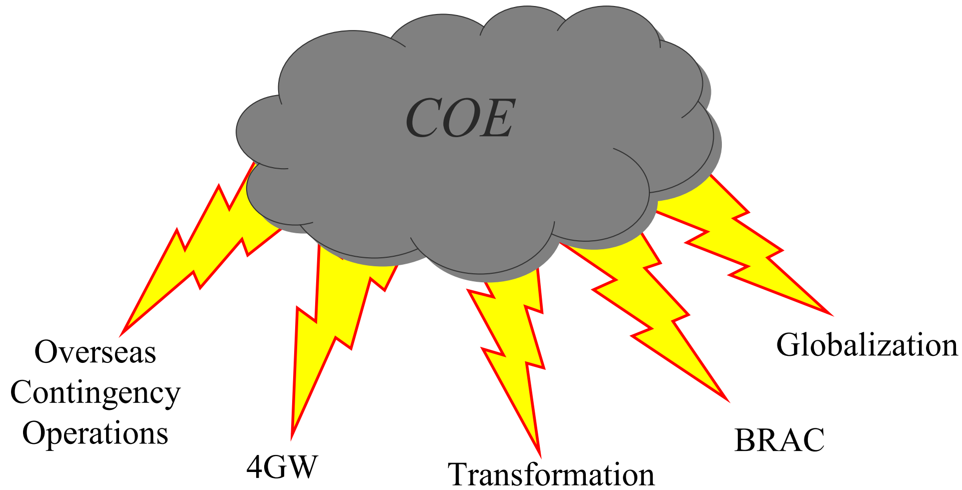

Figure 3: Competing demands and paradigm shifts for the U.S. military in the COE.

In addressing the critical issues dominating the COE, an advanced ground combat vehicle design should provide net worth at the various echelons of the military. Moreover, performance advantages in one area must be in concert with capabilities in others. In the pursuit of a technological advantage, the developer of a novel concept must simultaneously demonstrate capability overmatch against perceived threats while showing that the anticipated performance gains in maturing such a technology outweigh investing in an incremental advancement in the conventional means of delivering combat power. More simply stated, and especially apropo when dealing with an advanced weapon concept, the "bang for the buck" must be explicitly defined and clearly illustrated to the decision maker over several levels in analysis.

1.2.1 Generational Warfare Construct

When evaluating the COE, it is important to identify the significant changes in the nature of modern warfare. A paradigm shift that has spurred transformation in the armed forces of the 21st century is a movement from third-generation (3GW) to fourth-generation warfare (4GW).[7] The generational warfare construct helps organize the evolution of military affairs over time through identification of dominant themes in tactics, means, and weaponry. The four generations are collectively referred to as the manpower (first), firepower (second), maneuver (third), and information (fourth) generations of warfare. 4GW is typified by observations of combat in OIF and OEF. The main characteristic of this type of warfare is engagement with asymmetrical threats. These threats are networked and often operate on a noncontiguous, nonlinear battlefield, while representing some deeply rooted ideology.[8] Table 1 includes a brief categorization of the generational warfare construct to include the general characteristic, prevailing historical period, and notable examples for each generation.[9]

Table 1: Generations of Warfare

Generation	**Short Title**	**General Characteristic**	**Prevailing Period**	**Example**
First	1GW	Manpower	1000—1800	Waterloo
Second	2GW	Firepower	1800—1920	Maginot Line
Third	3GW	Maneuver	1920—1990	Blitzkrieg
Fourth	4GW	Information	1990—*2040*	9/11

[7] Thomas X. Hammes, *The Sling and The Stone: On War in the 21st Century* (Saint Paul, Minnesota: Zenith Press, 2004) 288-290.
[8] Harold A. Gould and Frank C. Spinney, "Fourth Generation Warfare" *Journal of Strategic Affairs* (September 2004) 7-12.
[9] The dates provided are to simply give the reader a reference in time for when that generation of warfare prevailed and are not intended to denote start and finish. Italicized entries are forecasted, e.g., the end of 4GW.

There are several important considerations to make for combat vehicle design with respect to the shift toward 4GW. First, the pace of change from generation to generation appears to be quickening. Figure 4 depicts a curve fit of this progressive trend for the generations of warfare represented by an exponential of the form in Equation 1 for the variable *t* in years. Second, the inherent uncertainty associated with operating in 4GW is, in many ways, greater than that seen in the previous generations. This operational ambiguity demands more robust design solutions that can adapt to the rapid evolutions in threat capabilities. Third, where ground vehicles once served as the virtual hubs for operations in maneuver warfare (3GW), in an information warfare domain (4GW) the platform fulfills a role within a larger and more integrated network of systems. Fourth, the compatibility between vehicle capabilities and requirements for 3GW versus 4GW is, in many ways, incongruent. In other words, the materiel requirements and definitions for military operation success in 3GW may not translate directly to 4GW.

$$GW(t) = 1 + 3.2\times10^{-5} e^{5.8\times10^{-5} t} \qquad \text{Equation 1}$$

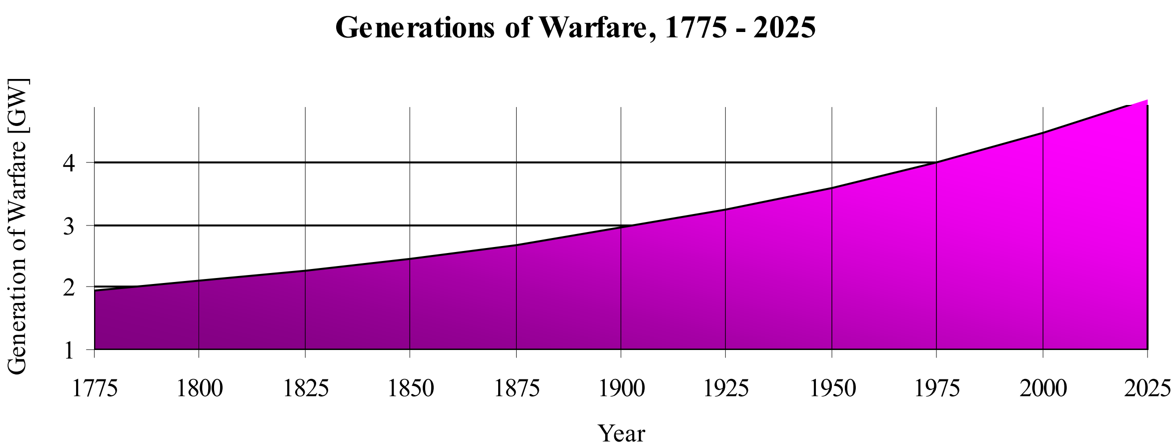

Figure 4: Generations of warfare progression during the last two centuries.

To build on this last point, the combat platforms or fighting vehicles designed for major combat operations (MCO), i.e., offensive and defensive operations in 3GW, were chiefly focused on decisively defeating a peer-threat on the battlefield. It remains to be seen what a satisfactory vehicle candidate embodies for the counterinsurgency (COIN) fights that dominate 4GW. Current platforms like the U.S. Stryker and Mine Resistant Ambush Protected (MRAP) vehicles have had mixed success in OIF and OEF due to a lack of protection and mobility, respectively. The U.S. Stryker and MRAP family of vehicles are also ill-suited for MCO for similar reasons. As will be further discussed, the evolution of these platforms over time has appeared to validate, or at least reaffirm, the need for sustenance of the three core characteristics of fighting vehicles, i.e., survivability, lethality, and mobility.

1.2.2 Puzzles and Mysteries

An additional shift related to the transition from 3GW to 4GW generation warfare deals with the notion of puzzles and mysteries. Puzzles are described as well-defined or well-structured problems where a solution is presumed to exist, whereas mysteries are described as ill-defined or ill-structured problems laden with high uncertainty and ambiguity. By these descriptions, the events surrounding a mystery have not played out through their entirety. The concept of puzzles and mysteries is well established in the national security arena, and recognition of the impact is understood in the defense materiel enterprise as well.[10] Puzzles typically have a definitive answer, the determination of which is dependent on the amount of information collected and

[10] Gregory F. Treverton, *Reshaping National Intelligence for an Age of Information* (New York: Cambridge University Press, 2004) 11-13.

processed. The classic example of a monumental puzzle tackled by a large organization is the Manhattan Project, the U.S. effort to develop an atom bomb during World War II.

On the other hand, a mystery can further be described as a problem to which there is no clear-cut resolution. Militarily, mysteries are often intertwined with the actions and reactions of the threat, and addressing them is more dependent on judgment and experience than the process-oriented methods that are employed to solve puzzles. The archetypal mystery from military history was how the U.S. could best deal with the scourge of German U-boats prowling the Atlantic during World War II. Acknowledging that this problem required a different approach, the War Department created the Tenth Fleet to mitigate the U-boat threat.[11] The tactics and procedures employed by the Tenth Fleet, though entirely different from that of the Manhattan Project, were eventually successful. More recently, this mystery-focused approach inspired the counter-improvised explosive device (C-IED) efforts in OIF and OEF led by the U.S. Joint IED Defeat Organization (JIEDDO).[12]

In the spirit of Newton's third law, but paramount to dealing with a mystery versus a puzzle, is simple acknowledgment that for every action there will be a reaction from the threat. From a technology perspective, recognizing where on the puzzle–mystery spectrum a problem rests is critical to developing a sound approach. When considering the generational warfare construct, military technologists in the COE often find themselves making decisions higher on the notional mystery axis on the puzzle-mystery spectrum.

[11] Montgomery C. Meigs, *Slide Rules and Submarines: American Scientists and Subsurface Warfare in World War II.* (Washington, D.C.; National Defense University Press, 1990) 112-114, 116. General (Retired) Meigs served as the director of JIEDDO.
[12] Adam Higginbotham, "U.S. Military Learns to Fight Deadliest Weapons" *Wired Magazine* (July 28, 2010). For a review of the decade of C-IED efforts led by the U.S., as well as an illustration of the iterative, dynamic nature of operating in a domain defined by mystery, see Noah Shachtman, "The Secret History of Iraq's Invisible War" *Wired Magazine* (June 14, 2011).

Table 2 provides a comparative overview of the qualities and characteristics defining puzzles and mysteries.[13]

Table 2: Qualities and Characteristics of Puzzles and Mysteries[14]

	Puzzle	**Mystery**
Conflict Era	Cold War	War on Terror
Generation of Warfare	third	fourth
Definitive Answer	yes	no
Value of Intelligence	high	moderate
Information Amount	high	moderate
Tense of Problem	past	future
Timescale	moderate	long
Influenceable	no	yes
Extent of Effort	solving	framing
Approach	process, procedure	judging, assessing
Dependent Upon	transmitter	receiver
Utility of Effort	detection	prevention
Use of Metrics	effective	elusive

[13] Gregory F. Treverton, "Risks and Riddles… Why We Need to Know the Difference" *Smithsonian Magazine* (June 2007) 72-78.

[14] Gregory F. Treverton, *Reshaping National Intelligence for an Age of Information* (New York: Cambridge University Press, 2004). The information presented in this table is based on Treverton's text, as well as commentary from Gladwell in his article from *the New Yorker*, "Open Secrets Enron, intelligence, and the perils of too much information: (January 8, 2007) and Treverton's *Smithsonian Magazine* article titled "Risks and Riddles The Soviet Union was a puzzle. Al Qaeda is a mystery. Why we need to know the difference" (June 2007).

Table 2 presents the information in an exclusionary fashion, but in practice, technological problems appear somewhere on a puzzle–mystery continuum. Few puzzle problems lack an element of mystery to them. Likewise, few mysteries fail to present the investigator with puzzles to solve. The effectiveness of a materiel solution strategy starts with careful consideration for this matter.[15] Contemporary threats present problems deep in the mystery region of the puzzle-mystery spectrum. This has challenged systems, processes, and procedures well suited to function against former threats predominately defined by puzzles.

Military technology researchers, like members of other industries evolving under the effects of globalization, are not simply conducting business as usual. The fiscal and operational demands on our armed forces have never been higher. Meanwhile, forecasting efforts anticipate even tighter budgets and continued operational demands. The change in focus from conventional, peer-threat, MCO in 3GW to a directed effort against asymmetrical threats, COIN operations, and 4GW has forced materiel developers to change the way they mature and field new technologies. Add to this an increase in the complexity and interconnectedness of modern ground combat systems, as well as the convergence and overall shrinkage of materiel developers in the commercial base of the military-industrial complex, and the scale of these challenges can be fully appreciated.[16]

[15] Malcolm Gladwell, "Open Secrets" *New Yorker Magazine* (January 8, 2007) 47-52, 117-119.

[16] Transcription of President Dwight Eisenhower's farewell address by Michael E. Eidenmuller. This speech, given on January 17, 1961, is considered to be the first use of the military-industrial complex term.

1.3 Motivation

A review of the contemporary DoD acquisition methods, as well as an assessment of combat vehicle successes and opportunities for improvement during the first decade of combat operations in OIF and OEF served as the motivation for this research. In consideration for the huge sums of money involved as well as the severity of the stakes—national security—defense acquisition is directed by a set of regulatory processes and procedures known collectively as the DoD 5000 Series.[17] Inspired by a succession of groundbreaking defense reform laws, most notably the Goldwater-Nichols Act of 1986, the Clinger-Cohen Act of 1996, and the Levin-McCain Act of 2009, the modern DoD 5000 Series would seemingly guarantee that technology endeavors produce capabilities on time, on budget, and with achievement of stated performance objectives.

The systems engineering rigor, political oversight, and voluminous technical requirements should predictably yield superior capability assessments and the pursuit of meaningful technologies. An assessment of the past 30 years shows an alarming trend; specifically, longer schedules and higher costs for acquisition projects to attain stated objectives (Figure 5). The reasons for this growth trend include the increased complexity of combat system designs, the changing nature of warfare, shifting requirements, and the budgetary intricacies of the acquisition process.

[17] Christopher H. Hanks, Elliot I. Axelband, Shuna Lindsay, Mohammed Rehan Malik, Brett D. Steele, *Reexamining Military Acquisition: Reform Are We There Yet?* (California: Rand Corporation, 2005) 28-35.

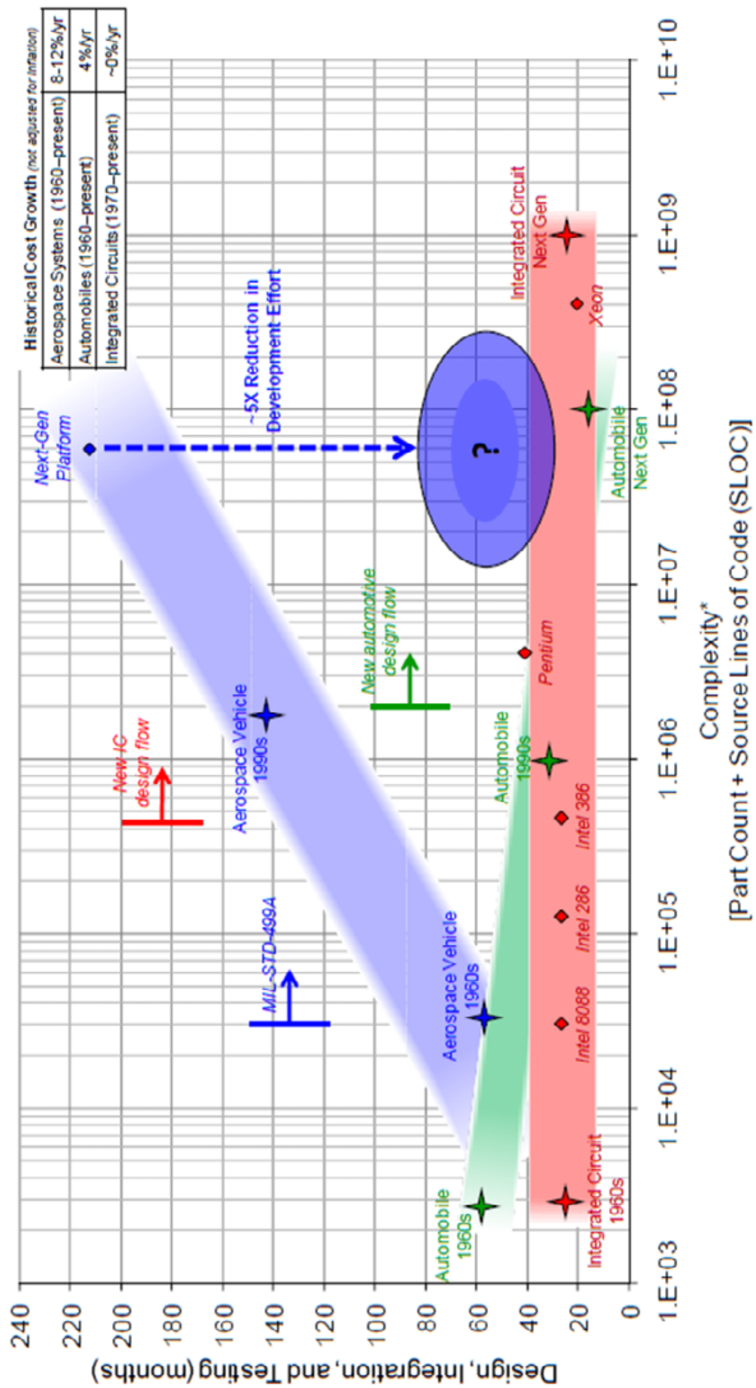

Figure 5: Development times: past, present, and future, with goals. General classifications for this data are from the automotive, commercial aircraft, and combat vehicle industries (source: DARPA AVM Information Briefing, October 7, 2010, Arlington, VA).

The trend for ground combat vehicle design in Figure 5 is also indicative of a shrinking military industrial base. Additionally, the reduced players in this industry are involved in endeavors that are not typically conducive with leveraging off commercial technology. This is in contrast with the automotive industry that gets to draw from the innovations of its competitors in both design and manufacturing practices. The accompanying discussion to this figure, led by the Defense Advanced Research Projects Agency (DARPA) Program Manager for the Adaptive Vehicle Make (AVM) program, included observation of increased program delay with increased system complexity. While discussing Figure 5, Paul Eremenko, the AVM Program Manager at DARPA, explained that the term used to denote complexity, i.e., the number of source lines of code (SLOC) plus the part count, was a first attempt to quantify the growing trend complexity by combining two dimensionless terms, i.e., SLOC plus part count. This complexity term was created to depict the voluminous software code incorporated into the operation of sophisticated electromechanical systems typical of most advanced military systems.[18]

Specifically for the U.S. Army and its acquisition community, the decade following 9/11 has been defined by a commendable record of breakthroughs and achievements for light infantry forces and unmanned aerial vehicles (UAVs), yet muted by a litany of major combat system cancellations and no-starts. The notable successes include more substantial and progressively lighter body armor, advanced personal weapon optics, the RQ-7A/B Shadow UAVs, and the M777 improved, lightweight towed 155 mm artillery piece.[19] On the downside, a partial list of cancellations includes Future

[18] Defense Advanced Research Projects Agency, "DARPA Aims to Revolutionize Defense Manufacturing" (Arlington, Virginia: DARPA, September 14, 2010).

[19] Peter W. Singer, *Wired for War: The Robotics Revolution and Conflict in the 21st Century.* (New York, New York: Penguin Press, 2009) 11-14.

Combat Systems (FCS), the Crusader self-propelled artillery vehicle, the RAH-66 Comanche stealth helicopter, and the Army Railgun Program.[20,21]

The pursuit of technology for the U.S. Army in the post 9/11 period has also been heavily focused on Counter-IED efforts ranging from detection to surviving an attack. Meanwhile, ground combat system capabilities have progressed incrementally atop aged legacy systems. The interim vehicle intended to bridge this legacy force with FCS, i.e., the Stryker, has incorporated protection-related modifications to address the threats persistent in 4GW. To fill the theater-specific survivability gap in OIF and OEF, the $20 billion MRAP program has clearly reduced casualties by dramatically increasing the crew survival rate from catastrophic IED incidents.[22] These MRAP vehicles, however, offer little to no inherent lethality or firepower capability. Moreover, the immense size of some variants limits their tactical mobility, particularly in areas with complex terrain, e.g. the types encountered with the topography in Afghanistan.[23]

Ten years of war focused predominantly on COIN, along with a decade of cancelled programs intended to fulfill future requirements, necessitate that the decisions made in the next opportunity cycle are cogent, comprehensive, and decisive. In acknowledgment to the originators and the proverbial "length of the teeth" in our ground-combat vehicle fleet, it should be noted that the Abrams M1 main battle tank and Bradley M2 infantry fighting vehicle (IFV) were fielded to the U.S. Army in the early 1980s after decades of research, design, testing, and eventual production. Modularity, programmed modernization activities, and unscheduled upgrades have extended the service life of

[20] Kris Osborn, "FCS Is Dead; Programs Live on U.S. Army to Dissolve Flagship Acquisition Effort" *Defense News* (May 2009).
[21] National Defense Authorization Act for Fiscal Year 2010 (Enrolled Bill [Final as Passed Both House and Senate, H. R. 2647—568 Title XLII—Research, Development, Test and Evaluation Sec. 201.
[22] Tom Donnelly, "Why Gates Is Wrong" *Armed Forces Journal* (June 2009).
[23] The range associated with these already subjective ratings is attributed to the fact that there are greater than 10 vehicles carrying the MRAP classification with variants for each, bringing the total even higher.

these battle-proven, and, in many respects, revolutionary designs. While these systems still reign supreme among peer threats—"tactical virtuosities" if you will—advancements in the succession of replacements appears modest, especially when measured against the leap in performance that both the Abrams and Bradley provided with respect to the platforms they supplanted in the force.[24]

On the same topic of ground combat vehicle progression, after the cancellation of the FCS program, the follow-on effort was halted over concerns about requirements, anticipated platform performance challenges, and the perennial concerns related to system cost and development schedule. Following this setback, the U.S. Army's restart for a combat vehicle replacement, known simply as the Ground Combat Vehicle (GCV), is currently being explored by a parallel and complementary, if not competing, effort by DARPA under the AVM program.[25] The AVM program has as a stated objective of, not only producing an advanced ground combat vehicle but at a higher level, demonstrating an acquisition design strategy of superior capacity and robustness that can handle the complexities inherent in engineering a ground combat system in a compressed and responsive timeline necessitated by the current operational demands and requirements.[26]

In short summary, all recent efforts by the U.S. Army acquisition community to produce the next-generation ground combat system have been cancelled outright or postponed successively. The defense industry trend for large programs of increasing complexity, lengthening schedules, and higher costs continues on an upward slope. This is truly a technological paradox. General understanding for the physical sciences in all disciplines of engineering is much higher today than during the combat vehicle design

[24] Bruce I. Gudmundsson, *On Armor* (London: Praeger, 2004) 174-176. Gundmundsson uses the term "tactical virtuosities".
[25] Paul Eremenko, Program Manager, Adaptive Vehicle Make (AVM), Tactical Technology Office Proposers' Day Briefing, 07 October 2010.
[26] Ibid.

heydays of the 1970s. The automation and efficiency afforded by computer aided design, rapid prototyping, and multi-physics modeling and simulation should at least enable projects today to match what looks in hindsight to be record pace for development.[27] Stated another way, what was impossible technologically in the past may be possible today, but what used to be possible programmatically (cost, schedule, and performance) is drifting further from reach in future design endeavors. Reasons for this trend may include more oversight and "players" in the decision loop, risk aversion, unstable funding, and perpetual shift in program requirements.

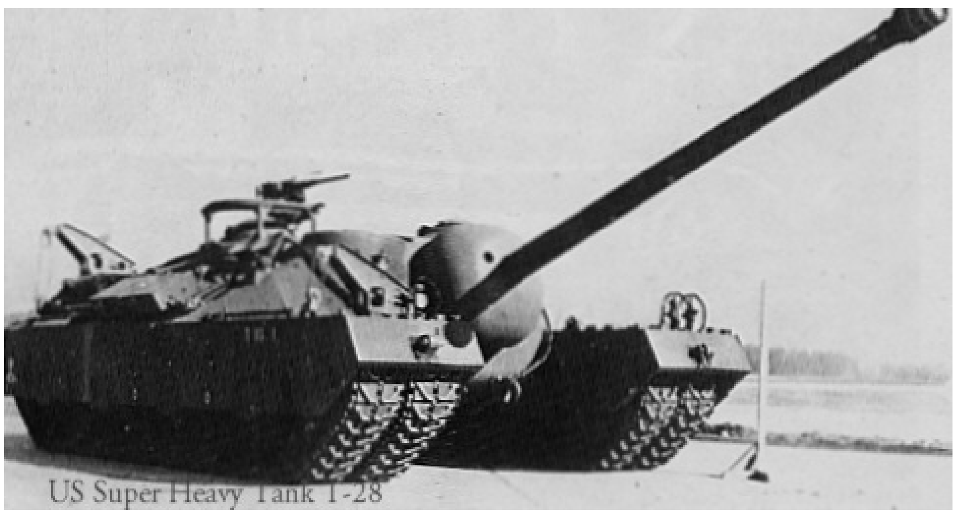

Figure 6: Photo of a U.S. T-28 Super Heavy Tank. Built as a prototype during World War II, this vehicle weighed over 86,000 kg (nearly 100 tons), was 11.1 m long and 4.39 m wide. Covered in a nearly complete shell of 30 cm armor, and sporting a 6.8 m long cannon, it required four sets of tracks (two on each side) to carry the immense load. The concept was abandoned for an inadequate level of mobility, as well as the immense logistical challenges associated with such a design.[28]

[27] Richard Chait, John Lyons, and Duncan Long, "Critical Technology Events in the Development of the Abrams Tank: Project Hindsight Revisited" (Washington, D.C.: National Defense University, 2005) 39-48.
[28] Source for photo is www. freeweapons-mod/images/t28-super-heavy-tank.

At their core, ground combat vehicles provide crewmembers with a mobile, protected source of firepower. A successor platform should provide advanced levels of those functional capabilities for future forces. In order to make the best decisions possible in the design and selection of the next ground combat vehicle, a focus on the attributes that make a ground combat system effective on the modern battlefield will serve to produce improved designs and better choices. With respect to these attributes, current practices may not be generating appropriately allocated designs. Additionally, a decade of focus on COIN has contributed to an imbalanced, possibly distorted, view on what attributes, traits, and metrics comprise a potent ground combat system. Over 10 years after fielding, the highly mobile, albeit lightly armed and inadequately protected, Stryker required upgrades to address its survivability on the battlefield (Figure 7).[29] On the other hand, the family of MRAP vehicles provided increased protection to the crew at the expense of mobility and lethality (Figure 8).

[29] Thomas E. White, Secretary of the Army, and General Eric K. Shinseki, (Joint Statement Before the Committee on Appropriations Subcommittee on Defense on the Fiscal Year 2002 Army Budget, Washington, D.C.: U.S. Senate, June 13, 2001) 3. Secretary White and General Shinseki were very clear in their testimony that the Stryker Brigade would lack sufficient lethality and survivability. As a bridge between the legacy and objective force, this interim platform represented a gap in capability.

 

Figure 7: U.S. M1126 Stryker as initially fielded (left) and after survivability improvements were instituted (right). Upgrades include appliqué armor, slat armor, gunner's protective shield, and C-IED jammers and emitters like the Rhino and counter-passive infrared and the Counter Radio-Controlled Electronic Warfare (CREW) Duke system.[30]

 

Figure 8: U.S. Armored High Mobility Multi-Wheeled Vehicle (HMMWV) (left) and the U.S. MaxxPro Mine Resistant Ambush Protected (MRAP) vehicle (right). The MRAP weighs 32,000 lbs, nearly three times that of the HMMWV. It stands over 12 feet tall, twice as high as the HMMWV.[31]

[30] Source for photos is www.military-today.com/apc/stryker.htm

[31] Source for the MRAP photo HMMWV photo is www.olive-drab.com/idphoto/id_photos_mrap_maxxpro.php and www.baesystems.com/m1114.html respectively.

1.4 Research Objectives

The design of a combat vehicle arguably represents the highest level of engineering difficulty and overall complexity that can be pursued in the defense materiel acquisition enterprise. Ground combat systems provide mounted warriors with movement, protection, and firepower. Moreover, modern fighting vehicles do so in spades, especially when compared to their World War II predecessors. From an automotive perspective, combat vehicles possess the off-road mobility of a high performance recreation vehicle, the operational range of a well-equipped family sedan, and some aspects of maneuverability akin to a sports car.[32] With respect to the protection afforded by these systems, combat vehicles shield crews with effective armor approximating that of a battleship, fire suppression systems rivaling those on racing vehicles, and redundant design of critical functions similar to what is done in aerospace design. On the armament or weapon aspect, combat vehicles shoulder an extensive quiver of weaponry ranging from 10 MJ direct fire cannons effective out to 5 km range, laser-guided missiles, fire control systems like those found in fighter aircraft, and optics with resolution comparable to a small reconnaissance UAV. These impressive performance specifications are made more so by how commonplace they have become in the international community of fighting vehicles and how durable and robust the designs must be to withstand the rigors of combat as demanded by the users and environment.

The purpose of this research was to explore the novel application of analytical and experimental methods that may improve the level of understanding concerning fighting vehicle design and selection. These proposed techniques may lend themselves to improved decision support tools that can contribute to better design efforts

[32] Tony Assenza, "M1A1 Abrams Main Battle Tank" *Car and Driver*, (May 2001). The U.S. M1 Abrams tank has pivot steering, allowing it to spin in place. It also has immense braking power.

and higher quality candidate vehicle selection processes. The face of warfare is changing at an increasing rate, and the future requirements for full spectrum operations will likely surpass those seen in the early part of the 21st century.[33]

The fundamental hypothesis of this manuscript is that decision support tools formulated around the principal attributes of survivability, lethality, and mobility, can enhance the design and subsequent selection of ground combat vehicles. By steadfastly focusing on the attributes that matter most, and adding a dimension to the analysis with screening at the various levels of war, the current processes may be improved. Critical to this study is appreciating the competing demands between and within the principal attributes while investigating the interactions and performance effects related to system survivability, lethality, and mobility.

In order to explore this hypothesis, a series of related research questions was investigated. **Question 1: What effect does the use of decision support tools built around the principal attributes of survivability, lethality, and mobility, have on combat vehicle selection? Question 2: What are the relative contributions and interactions of survivability, lethality, and mobility to ground combat vehicle performance?**[34] **Question 3: How does this methodology lend itself to the comparison of the evolutionary development of conventional powder gun cannonry versus a revolutionary weapon concept like the railgun?**

Chapter 2 establishes the conceptual framework for this manuscript by defining the principal attributes, secondary traits, and tertiary metrics associated with survivability, lethality, and mobility. Sources for this foundation include applicable

[33] Paul H. Deitz, Harry L. Reed Jr., J. Terrence Klopcic, James N. Walbert, *Fundamentals of Ground Combat System Ballistic Vulnerability and Survivability* (Reston, Virginia: American Institute of Aeronautics and Astronautics, 2009) 2-4.
[34] R.M. Ogorkiewicz, *Design and Development of Fighting Vehicles* (New York: Doubleday and Company, 1968) 132-140.

literature, previous work, military doctrine, and analogous design efforts. This chapter also explores the layering of these attributes at the three levels of war: tactical, operational, and strategic. This exploration includes scaling analysis of mass, length, and time for the principal attributes at the three levels. The scaling analysis is presented from the notional deployment and subsequent engagement of a combat vehicle against a peer threat system. Chapter 2 concludes with a comparison of the merits of a group of fielded platforms using the survivability, lethality, and mobility attributes at the various levels of war. This was done in order to qualify both the complementary and the competing demands between attributes. The qualification of these relationships is displayed using the top portion of the quality function deployment (QFD) chart. The scaling and QFD analysis for the principal attributes at the levels of war are presented as a point of departure to qualitatively demonstrate the competing demands and inherent conflicts between design considerations horizontally (among attributes) and vertically (throughout the levels of war).

Chapter 3 addresses the first research question with the development and subsequent use of an attribute-based network to apply weightings to prototypic ground combat vehicles. The results of an attribute weighting and candidate vehicle selection survey exercise using two distinct groups of U.S. Army officers are discussed. This chapter provides insight regarding the individual prioritization and relative subjective weighting assessments of fighting vehicle attributes. The data presented is a direct reflection of a representative population of mid-career U.S. Army officers, the vast majority of which have served in combat and are working in related fields within the Acquisition Corps, the technical procurement field of the U.S. Army. The information presented depicts the value that contemporary warfighters place on fighting vehicle attributes, and how decision support tools can assist (or interfere) with presentation of specification data for decision making.

Chapter 4 explores the effects and interactions of the principal attributes using both design of experiment (DOE) and analysis of variance (ANOVA) methods. This chapter focuses on the second research question by rendering and testing an experimental set of prototypic vehicles in a multifactorial, multilevel DOE/ANOVA test matrix. The relative performance of these vehicles as fought in the JRATS (Joint Reconnaissance and Targeting System) simulation—a virtual reality, physics-based, robotic combat vehicle prototyping environment, are reported and discussed.[35] The mean performance for each vehicle variant from a series of 1,600 independent simulated combat missions (approximately 100 missions per platform variant) is presented. The attribute interactions are classified using a residual analysis statistical method commonly used in ANOVA methods. Military vehicle screening criteria are often based on spatial, mass, schedule, and financial limits. Chapter 4 includes insights gleaned from the preceding work to better utilize the physical weight and financial constraints placed upon developmental systems. When a program is presented with a budgetary surplus, or more likely, if a reduction is imposed, knowledge of the relative attribute effects and their interactions has the potential to direct where to make cuts, as well as those system attributes that must be defended in order to sustain effective performance.

Chapter 5 builds on the previous findings regarding combat vehicle attribute net effects to formulate a trade study comparing conventional powder gun cannonry and the railgun class of electromagnetic weapons. When faced with a notional advanced tank and infantry fighting vehicle threat, direct fire concepts were prototypically designed and

[35] JRATS is used within the U.S. Defense Acquisition University (DAU) for the capstone design exercise in the Level III Program Management Course, PMT 352. Derived from the Cognitoy LLC Mindrover 1.108 space-based autonomous robotic vehicle design program, the military version enables the user to expediently create and fight notional robotic vehicles in an urban environment.

subsequently analyzed to answer the third research question regarding conventional cannonry and electromagnetic launch. Conventional systems were developed in parallel with the advanced concepts in order to highlight the costs associated with improving upon mature technologies versus pursuing a new frontier in weaponry. This chapter concludes with the technical requirements and performance objectives for a future direct fire railgun system.

Chapter 6 provides a general summary for this manuscript highlighting the main points from the preceding chapters. This chapter attempts to underscore the central theme of principal attribute significance in fighting vehicle analysis, as well as to unify early subjective observations with the objective analysis of the experimental data sets. It includes references to the motivations for this research as well as the most salient learning points gleaned from this pursuit. Chapter 7 includes a list of future work opportunities representing areas of interest not able to be addressed within the limits of this research program. This list corresponds to work areas referenced within each of the main chapters.

1.4 Literature Review

The literature review for this dissertation included an investigation of two main subjects: multicriteria decision making (MCDM) analysis and the engineering considerations for ground combat vehicle design. Supporting work in the decision making arena fell into both the multiobjective and multiattribute decision analysis categories. Multiobjective decision making (MODM) analysis deals with design and formulation efforts and the subsequent choosing of a strategy from a virtually infinite set, while the multiattribute (MADM) version deals with candidate selection from a finite set. Both MODM and MADM contribute to the military decision making process and the analysis of alternatives methods used in the operational U.S. Army and Acquisition Corps respectively. Additionally, many areas of the Operations Research and Systems Analysis (ORSA) military career field rely on these approaches to guide strategic and operational decision making.[36]

[36] The Military Applications Society (MAS) is a technical society within the Institute for Operations Research and the Management Sciences (INFORMS).

Table 3: Distinctions Between MADM and MODM[37]

	MADM Multiattribute Decision Making	**MODM Multiobjective Decision Making**
Criteria Defined By	attributes	objectives
Objectives	implicit	explicit
Attributes	explicit	implicit
Constraint	inactive	active
Alternatives	finite	infinite
Decision Maker Interaction	moderate	high
Usage	selection	design

With respect to fighting platforms, the theory, design, and selection of ground combat vehicles is largely focused on the automotive/heavy equipment considerations for mobility, coupled with military considerations for survivability and lethality analysis. The topic of mobility was well represented in both military and academic literature. For example, the Society of Automotive Engineers (SAE) produce an annual journal edition dedicated solely to military mobility and transportation research. Works on lethality research are limited somewhat to conference proceedings on ballistics, impact physics, and weapon analysis. For security and proprietary reasons, only general aspects of survivability advancements are available in open sources.

[37] Table derived from K. Paul Yoon and Ching-Lai Hwang, *Multiple Objective Decision Making* (California: Sage Publications, 1995) as well as Ching-Lai Hwang and Kwangsun Yoon, *Multiple Attribute Decision Making, Methods and Applications* (New York: Springer-Verlag, 1981).

The literature review focused on these two broad subjects, MCDM analysis and combat vehicle design, especially on works that addressed the intersection of these two areas, i.e., MCDM analysis dealing with the design and/or selection of ground combat vehicles. Defense-related surrogate case studies, e.g., military aircraft design and selection efforts, were also analyzed.

1.4.1 Multicriteria Decision Making Analysis

The pioneering work of Ronald Howard, one of the founding fathers of the decision analysis field, was reviewed from the aptly titled *Principles and Applications of Decision Analysis.* His efforts were among the first to define the emerging field of decision analysis as one that can "focus logical power to reduce confusing and worrisome problems to their elemental form."[38] In his manuscript, the decision analysis process is described as being iterative in nature and comprising deterministic, probabilistic, informational, and decision making phases, with a recursive loop for gathering new information and reentering the process (Figure 9).[39]

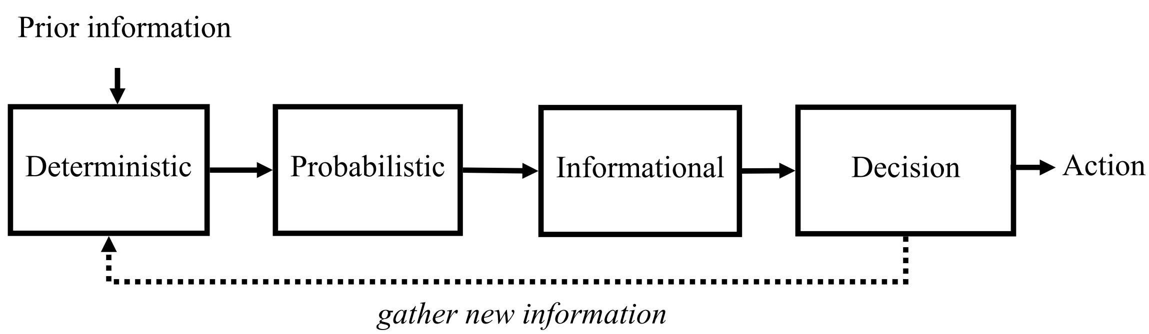

Figure 9: Howard's decision analysis cycle diagram.

[38] Ronald A. Howard, James E. Matheson, *The Principles and Applications of Decision Analysis* (California: Strategic Decisions Press, 1989) 21.
[39] Ibid., 26.

Howard also developed the useful decision analysis hierarchy along with the concept of how critical a role uncertainty plays in the process. Most helpful for this study was the collection of MCDM texts, published as compilations of journal papers. The MADM version codified the noncompensatory and compensatory models used to distinguish between those systems that do not permit tradeoffs between attributes and those that do, respectively.[40] This work also provided a methodology for transformation of attributes, accepting quantitative and qualitative (fuzzy) data with ordinal, interval, and ratio scales.[41] Within this MADM journal collection is a valuable discussion about conjunctive (or satisficing methods) versus disjunctive (or the quest for the candidate of greatest perceived value) methods.[42]

Of particular value to this research was a review of the seminal works of Thomas Saaty and the analytic hierarchy process (AHP). AHP endures to this day in practice as a method of formalizing complex systems and relationships using a hierarchical structure. The essence of AHP is to enable the decision maker to visually structure a MADM problem.[43] Saaty's AHP has served as the basis for adding value to numerous military projects, to include fighter aircraft selection, theater-level logistical processes, and improved use of resources for military recruiting.[44] Numerous methods and accompanying software programs have been developed in the MADM field, including DECMAT, ELECTRE, Expert Choice®, LDW®, TOPSIS, TreeAge®, and Squidmat. Of special note, Richard Stikkers' DECMAT (which was used here) was developed for the

[40] Ching-Lai Hwang, Kwangsun Yoon, *Multiple Attribute Decision Making, Methods and Applications* (New York: Springer-Verlag, 1981) 24-28.
[41] S. Stevens, *Measurement- Definitions and Theories* (New York: Wiley, 1959) 18-63.
[42] Hwang, 71.
[43] K. Paul Yoon, Ching-Lai Hwang, *Multiple Objective Decision Making* (California: Sage Publications, 1995) 59-65.
[44] T. L. Saaty, *The Analytic Hierarchy Process* (New York: McGraw Hill, 1980).

U.S. Army and played a role within the analysis of alternatives process taught at the Command and General Staff College.[45] Joe Stauffer later developed the complementary Squidmat tool that addressed some of the DECMAT limitations by conversion of all values to a *z*-ranking; it also avoids the pairwise rating scheme for attribute weightings.

While methods and software abound in the field of MCDM, Yoon and Hwang surveyed a range of titles and concluded that "the choice of a [specific] method is not crucial enough for many [decision makers] to be overly concerned about it."[46] Comparative studies considering collections of methods and computational aids produced similar decision analysis results, confirming their collective recommendation to establish a "goal hierarchy approach to generate attributes and sub-attributes."[47]

The MODM publication version focused on the use of objective and utility functions in conjunction with linear and nonlinear goal programming to converge on an optimal or satisficing candidate course of action. Among the concepts presented were those dealing with optimal solutions, where the vector maximum problem is one "which results in the maximum value of each of the objective functions simultaneously."[48] This, as opposed to the nondominated solution, or one in which "no one objective function can be improved without a simultaneous detriment to at least one of the other objectives of the [vector maximum problem]." These are also known as Pareto-optimal solutions, noninferior solutions, or efficient solutions. Four classes of MODM methods were presented in this work; they are clearly defined by the state at which information is

[45] Richard B. Stikkers *DECMAT*. Stikkers wrote this program as a captain in the U.S. Army; he is now a defense contractor at Raytheon. His expertise was very helpful, particularly the information shared through a series of emails in which he described the mathematical basis and supporting documentation for the pairwise rating, attribute weighting generation, and consistency ratio calculations.

[46] K. Paul Yoon, Ching-Lai Hwang, *Multiple Objective Decision Making* (California: Sage Publications, 1995) 68-72.

[47] Yoon, 72.

[48] Ching-Lai Hwang, Kwangsun Yoon, *Multiple Attribute Decision Making, Methods and Applications* (New York: Springer-Verlag, 1981)16.

needed. These include: no preference articulation, *a priori* preference articulation, progressive (running-iterative) preference articulation, an *a posteriori* preference articulation.

In most processes, the creators begin by identifying the problem, and subsequently drafting the appropriate objectives to be used in addressing it.[49] Ralph Keeney, another highly respected figure in the field of MCDM, argued that it is best to first codify the organization's central values and objectives, and then look for ways to achieve them.[50, 51] In his book *Value Focused Thinking*, he argues that too often, decision making processes center on choosing among alternatives, when in fact the focus should be on the organization's values and principles. In other words, Keeney's methods focus on deciding what end state is desired, then working backward to design a solution and framework conducive with achieving that objective. In reviewing the various methods, Jonathan Bard showcased the two prominent multicriteria methodologies as applied to the U.S. Army's selection process for rough terrain cargo handling equipment.[52] This reference demonstrated several approaches for deconstructing a choice problem using 12 attributes, as well as the opportunities and challenges of the different techniques. The comparative case studies as well as the notable references for the analytic hierarchy process (AHP) and multiattribute utility theory (MAUT) were used to build Table 4, a list of the highlighted differences between the two main decision analysis methods.

[49] Robert T. Clemen, *Making Hard Decisions: An Introduction to Decision Analysis*, Second Edition (Belmont, California: Wadsworth, 1996) 6-15.
[50] R. Keeney, *Value-Focused Thinking* (Cambridge, Massachusetts: Harvard University Press, 1992).
[51] R. Keeney and H. Raiffa, *Decisions with Multiple Objectives* (New York: Wiley, 1976).
[52] Jonathan F. Bard, "A Comparison of the Analytic Hierarchy Process with Multiattribute Utility Theory: A Case Study" IIE Transactions, Volume 24, Issue 5, 1992, 111-121.

Table 4: Comparison of the Analytic Hierarchy Process (AHP) and Multiattribute Utility Theory (MAUT)

	AHP	**MAUT**
Scaling	ratio; priorities	interval; utilities
Preference Elicitation	pairwise comparison, ordinal and ratio	tradeoffs among alternatives
Weighting	normalized ratio via eigenvalues	assigned values, specified intervals
Synthesis	additive, eigenvectors	additive, multiplicative
Structure	hierarchical	matrixes or tree
Built-in Feedback	consistency	synthesis
Ease of Use	simple	complex
Level of Abstraction	low	high
Outcomes Measured	subjective scale	objective value
Number of Attributes (limit)	moderate (7)	high (10+)
Number of Alternatives (limit)	moderate (7)	high (10+)
Used Mainly By	general consulting, industry, government	specific consulting, industry, academia
General Public Use	yes	no
Theory and Rules	minimal	demanding
Credited To	Saaty	Keeney and Raiffa

The comparative case studies as well as the notable references for the analytic hierarchy process (AHP) and multiattribute utility theory (MAUT) were used to compile the information found in Table 4.

1.4.2 Ground Combat Vehicle Theory and Design

The foundation of the literature review on ground combat vehicle theory and design was provided by the pioneering work of Richard Ogorkiewicz. While there are numerous historical works on the topic of combat vehicles and the military utility of employing them, Ogorkiewicz is one of the few to formally codify the theory and design of combat vehicles into a reference book. His first work, *Design and Development of Fighting Vehicles*, provided an overview of ground combat system fundamentals to include weapons, turret and hull construction, and the automotive aspects of both wheeled and tracked platforms.[53] Around the same time of the publication of this work, the U.S. Army Materiel Command (AMC) produced an extensive library of Engineering Design Handbooks. Available through the U.S. Defense Technical Information Center (DTIC), these important reference manuals contain an expansive, albeit somewhat dated, collection of the scientific underpinnings for an assortment of military vehicle design specialties. A partial list of relevant handbooks is provided in Table 5. Even at the present, Ogorkiewicz and others repeatedly reference these works. If the handbook series has since been modernized, it has taken a form not linked to DTIC and elusive to research queries, both open and internal to the military.

[53] R.M. Ogorkiewicz, *Design and Development of Fighting Vehicles* (New York: Doubleday, 1968).

Table 5: Pertinent U.S. Army Materiel Command Engineering Design Handbooks

Number	**Title**
AMCP 706-106—108	Elements of Armament Engineering, Parts I, II and III
AMCP 706-170	Armor and Its Application to Vehicles
AMCP 706-250, 252	Guns – General and Gun Tubes
AMCP 706-355	Automotive Assembly and Design
AMCP 706-342	Recoil Systems
AMCP 706-140	Trajectories, Differential Effects, and Projectiles
AMCP 706-150	Interior Ballistics of Guns
AMCP 706-331	Fire Control Systems
AMCP 706-340	Carriages and Mounts

Ogorkiewicz later produced a much more detailed, two-volume set that provided the defense community with an even richer engineering and scientific discussion related to the technology and design of fighting vehicles.[54] In his text, Ogorkiewicz built upon the seminal works of M.G. Bekker and his research on land locomotion and terrain-vehicle systems.[55] Bekker's works are credited with providing the U.S. Army with foundational theories on land locomotion and terramechanics. Ogorkiewicz also referenced the works of Manfred Held with respect to armor design and development. Held was one of the originators of explosive reactive armor (ERA), as well as a pioneer in the design and theory of shape charge munitions.

From the nested relationship of vulnerability and lethality, Paul Deitz co-authored the AIAA book titled *Fundamentals of Ground Combat System Ballistic Vulnerability*

[54] R.M. Ogorkiewicz, *Technology of Tanks* (United Kingdom: Jane's Information Group, 1991).
[55] Mieczyslaw Gregory Bekker, *Introduction to Terrain-Vehicle Systems* (Ann Arbor, Michigan: University of Michigan Press, 1969).

and Lethality.[56] This book may be the only contemporary work solely dedicated to the topic of fighting vehicle protection and firepower, particularly with respect to research and engineering. Deitz and his coauthors collaborated extensively for this work, and the list of contributors illustrates the breadth and depth of defense-related research reviewed to develop this resource. Within this title is a description of the "means and missions framework"—an iterative process for evaluating system lethality and vulnerability in the context of an engagement scenario.

Finally, the respected handbook on weaponry by the German arms manufacturer Rhienmetall (arms manufacturer name, not author), as well as Don Carlucci's three-volume set on ballistics, was reviewed in detail. Carlucci covered the main areas of internal, external, and terminal ballistics in his book, expanding on the general framework provided in the Rhienmetall version. Carlucci's work is a stand alone reference well suited for the study of conventional, powder gun cannonry.

1.4.3 Ongoing Complementary Work

As of this writing, there are two contemporary efforts related to the work described in this manuscript. William Nanry of Lockheed Martin has developed and presented a decision support tool called *Econometric Frontier Analysis*.[57] Nanry's focus was to provide corporate leadership with a way of quantifying and visualizing the potential gains (business and military) and underlying risks (again, business and military) associated with novel military technologies and concepts. His technique derives future capabilities and operational requirements from strategic documents like the Quadrennial

[56] Paul H. Deitz, Harry L. Reed Jr., J. Terrence Klopcic, and James N. Walbert, *Fundamentals of Ground Combat System Ballistic Vulnerability/Lethality* (Reston, Virginia: AIAA, 2009).

[57] William Nanry, formerly a colonel in the U.S. Army, is now a research scientist at Lockheed Martin. Several informal discussions following a seminar he presented at the University of Texas in Austin in September 2010 indicated areas of inclusiveness and novelty in respective efforts.

Defense Review and Joint Vision statements. The information divined from these documents serves as the entry point for investigating novel technologies conducive with those strategic objectives.[58] In other words, it is a top-down method that screens candidate concepts based on merit at the highest echelon of command. Value and risk are then visually depicted on a planar surface, with one axis representing the commercial worth of a pursuit, and the other representing military value for employment of the technology. The main focus of this method is on the civilian and military decision makers at the highest levels of the authority.

Solely related to the U.S. Army GCV project, DARPA formed the Adaptive Vehicle Make (AVM) program in late 2009. The anticipated product from the AVM project is the Fast Adaptable Next-Generation combat vehicle (FANG). Broad and ambitious in virtually every way, one of the stated goals of the program is "to make a dramatic improvement on the existing systems engineering, integration, and testing process for defense systems." Paul Eremenko, the AVM program manager, attributes the systemic problems in defense development enterprises as related to an inability to handle the increasing complexity associated with modern combat systems (Figure 5). He bases this assessment on an observation that, while other industries, e.g., commercial aerospace, automotive, computer processor, have embraced and leveraged design automation and sophisticated modeling techniques, the military and its associated design efforts have not pursued these areas with the same sense of urgency.

With respect to the assessment of risk and technological maturity, the DoD has an established technology readiness level (TRL) matrix (Appendix 1). Based on an earlier version developed by NASA, this matrix helps position an emerging concept along a scale commensurate with the level of development. Missed opportunities to or failure to

[58] R. Keeney, *Value-Focused Thinking* (Cambridge, Massachusetts: Harvard University Press, 1992) 72.

properly mature new technologies in the science and technology (S&T), or laboratory environment almost invariably leads to cost and schedule over-runs in acquisition weapons system programs.[59] The TRL methodology helps identify areas of risk by converting subjective assessments of maturity into an objective score used to quantify the level of development.

[59] Government Accounting Office, "Better Management of Technology Development Can Improve Weapon System Outcomes" GAO/NSIAD-99-162, (United States General Accounting Office, July 30, 1999) 12.

1.5 Lessons Learned

- The U.S. Army legacy systems, e.g., the Bradley infantry fighting vehicle, are a tribute to the tremendous technical effort made during the Cold War. However, vehicle design pursuits in the post Cold War era have been challenged to rapidly evolve based on emerging threats, in many cases demonstrating a need to refocus on and include deeper consideration for the essential, core characteristics of a fighting vehicle, i.e., survivability, lethality, and mobility.
- The rate of change with respect to the evolution of warfare seems to be increasing. The threats faced by the U.S., operating within a global network and aided by a massive exchange of information, have pushed the speed of development and challenged traditional processes for military technology developers.
- Contemporary requirements appear to be defined more by mysteries than puzzles. Related to the rapid pace of evolving needs, materiel solutions need more inherent robustness to help underwrite the high uncertainty associated with future pursuits.
- Contemporary efforts in the arena of ground combat vehicle design are focused on decision makers, return on investment, and the manufacturing and design process rather than on a defined threat (puzzle) or addressing the inherent operational uncertainties (mystery).
- The field of decision analysis has been exercised in previous military efforts to good effect. This multi-disciplinary field offers an array of techniques and approaches designed to enrich the quality of decision making efforts.
- There is a rich and comprehensive history of combat vehicle design theory and technical reference that appears to have peaked in volume during the Cold War.

1.6 Conclusions

The tools and techniques available in support of multiattribute decision making are plentiful and well developed, with some applicable learning curve associated with each. The volume of literature associated with the theory of fighting vehicles appears to have peaked with the end of the Cold War. Progress in this field was made during the developmental phases of the U.S. Future Combat Systems (FCS) program, but its cancellation may have halted any significant momentum in this field. With this understanding, it is unclear how much progress has truly been made with respect to conceiving replacement platforms possessing a revolutionary, versus evolutionary, scale of performance advantage over existing legacy ground combat systems. The urgent demands of current overseas contingency operations has encouraged the pursuit of candidate systems that are focused on dealing with an asymmetrical threat, e.g., MRAP, for protecting against IEDs.

In conclusion, the literature review conducted for this work was focused on the development of decision support tools aimed at improving the state of the art with respect to future ground combat vehicles. The two main areas investigated, decision analysis and ground combat vehicle design, provided a deep appreciation for the extensive and lasting contributions from respected pioneers in the fields of decision analysis and the theory of fighting vehicles. The scarcity of information linking the ground combat vehicle design and decision analysis was used to develop research questions that could contribute to the base of knowledge in combat vehicle design theory. In other words, the research questions were created in a focused effort to form assistive and meaningful conceptual bridges between decision analysis and ground combat vehicle design.

Chapter 2: Ground Combat Vehicle Design Characteristics and Operational Considerations

> We see…that the theory of probability is no more than a calculus based on good sense…The theory leaves nothing arbitrary in choosing opinions or in making decisions, and we can always select, with the help of this theory, the most advantageous choice on our own. It is a refreshing supplement to the ignorance and feebleness of the human mind.
>
> …the theory gives the surest insight which can guide us in our judgment and teaches us to keep ourselves from the illusions that often mislead us, …there is no other science that is more worthy of our meditation.
>
> —Marquis de Laplace, *The Analytical Theory of Probability*, 1812 [60]

2.1 Introduction

This chapter provides the organizational framework for the decision support tools developed in this manuscript. This framework was created by thoroughly defining, exploring, and evaluating the core characteristics of a ground combat vehicle horizontally in the context of various operational demands and vertically throughout the levels of war. As a point of departure, the critical characteristics of combat vehicle, i.e., survivability, lethality, and mobility, were fully defined and parsed to secondary traits and tertiary metrics. At a qualitative level of analysis, competing demands and complementary relationships were identified. The review of the operational considerations for full spectrum operations reinforced the enduring value of ground combat vehicles in future warfare. More importantly, the identified conflictions and synergisms for ground combat vehicle considerations provided the focal points for further investigation with respect to the selection and design of fighting vehicles.

[60] Dr. Eric Bickel of the University of Texas at Austin, presented this Laplace quote during a January 2011 ORI397 Decision Analysis class lecture.

2.2 General Approach

At the core of their functional capability requirements, well-equipped ground combat vehicles provide the crews that fight them with a highly mobile, well-protected, decidedly lethal weapon system. In this chapter, a decision support framework for ground combat vehicles was developed with a deliberate appreciation, as well as a steadfast focus on, these critical capabilities. This framework has as its foundation the combat vehicle principal attributes of survivability, lethality, and mobility. Since most multiattribute decision making processes adopt a hierarchy or branched network to scope the problem, a similar approach was used here concerning these important fighting vehicle capabilities. In recognition of Keeney's emphasis on first articulating values and identifying organizational principles, this process began with a survey of the doctrinal basis for military operations, focused on those instances where ground combat vehicles add utility. If the traditional approach is to build a hierarchy resembling a tree, where the trunk represents the objective and the main branches represent the first level attributes, Keeney's approach would recommend beginning with the soil and roots, where the main roots feeding the trunk would represent the guiding principles.

Continuing with this analogy, the foundational analysis, or creation of the root system if you will, focused on the considerations involved in the four major types of combat force employment encompassing what is known as full spectrum operations (FSO). These four types are referred to as offensive, defensive, stability, and civil support operations. Foundational analysis also included a review of the doctrinal elements of combat power. These initial investigative efforts helped codify the utility of a ground combat vehicle in the contemporary operating environment. To aid in the refinement of this concept, the framework incorporated consideration of these attributes at the tactical, operational, and strategic levels of war. This chapter is intended to serve as an initial step in developing a basis for framing the incredibly complex problem of designing and selecting advanced ground combat vehicle successors to the current legacy systems.

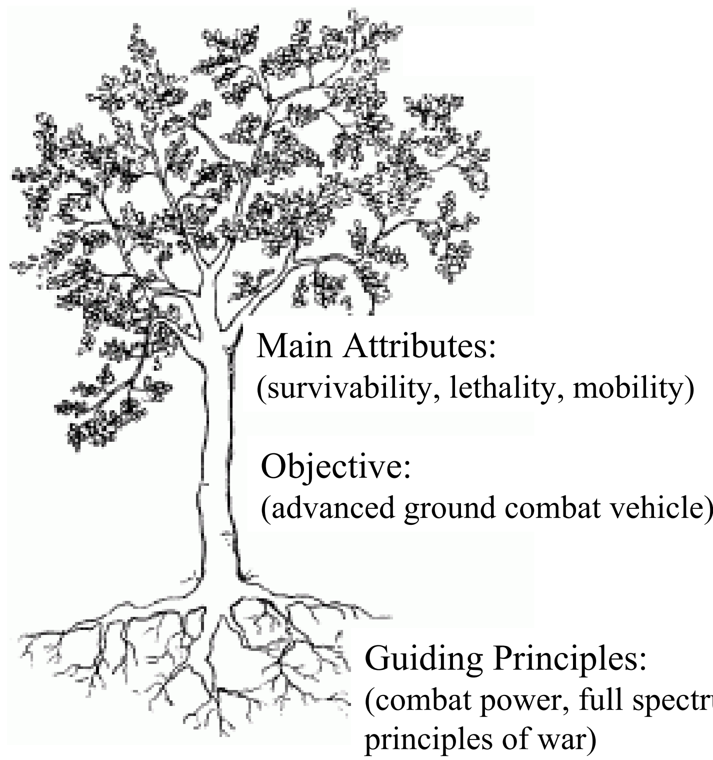

Figure 10: Graphical analogy of a decision attribute hierarchy to include foundational considerations.[61]

2.2.1 Decision Theory

A decision can be simply described as the irrevocable allocation of resources.[62] Within the constraints of a complex problem, there are many aspects of decision making that create dilemmas for the decision maker. For example, issues of scale, information quantity versus quality, and parameter uncertainty all create general angst for designers

[61] Source for tree graphic is www.comminit.com; text by the author.
[62] Ronald A. Howard, James E. Matheson, *The Principles and Applications of Decision Analysis* (California: Strategic Decisions Press, 1989) 23.

and decision makers. Good decisions often pass the proverbial test of time; that is, the merit of the decision withstands the inherent unknown of the future, i.e., accounts for a certain level of uncertainty. Upon inspection of the decision analysis flowchart (Figure 11), this success can be attributed to prudent and thorough sensitivity analysis.[63] In other words, the war gaming and hypothetical "what if" questioning exercises are vigorously engaged and fully explored.[64] A robust decision, which is necessarily less sensitive to the inherent uncertainty of the future, sustains greater value over time.

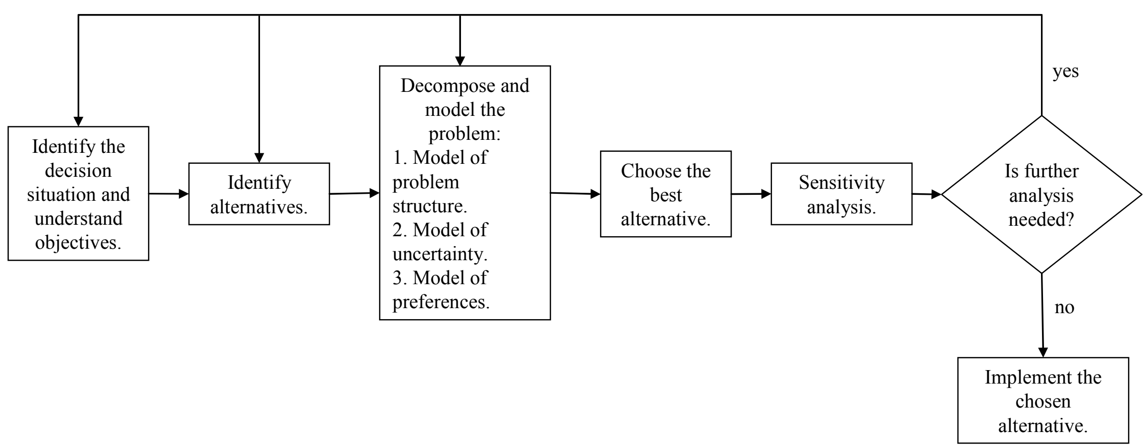

Figure 11: Decision-analysis process flowchart.

2.2.2 Background on Fighting Vehicles

The creation of the framework began with a review of those aspects of combat vehicle design most conducive with creating the conditions for a good decision in the eventual selection of a successor to the current legacy system, i.e., the U.S. M2 Bradley infantry fighting vehicle (IFV). The contemporary operating environment, previously

[63] Robert T. Clemen, Making Hard Decisions: An Introduction to Decision Analysis, Second Edition (Belmont, California: Wadsworth, 1996) 6-15.
[64] Ibid., 156.

defined as the "composite of the conditions, circumstances, and influences that affect the employment of capabilities and bear on the decisions of the commander" is laden with competing demands and enduring challenges. An assessment of both the role of the combat platform in full spectrum operations, as well as the elements of combat power, served to catalog what functionality a ground combat vehicle brings to the battlefield. This step aided in creating the foundation for the decision analysis process, i.e., identifying the situation and understanding the purpose and objectives.[65]

The U.S. DoD dictionary of terms defines a ground combat vehicle as a "means of ground transportation, with or without armor, designed for a specific fighting function."[66] *Jane's Armour and Artillery*, a respected source of defense related information, classifies these functions by categorizing platforms into five main types with accompanying subtypes as needed (Figure 12).[67] Combat vehicles, especially those equipped with capable weapon systems, are also commonly referred to as fighting vehicles.[68] Within the defense community, the term *armored personnel carriers* (APCs) includes the more heavily armed IFVs like the U.S. M2 Bradley and Russian BMP-3 Kurgan. Concepts for the U.S. Army's current ground combat vehicle (GCV) program embody performance requirements akin to an IFV. Therefore, in the context of this manuscript, the term *ground combat vehicle* refers to a vehicle, either tracked or wheeled, performing the role of an IFV or heavily armed APC. At its core, the ground combat vehicle provides crewmembers with a mobile, protected, weapon system with overall performance

[65] R. Keeney, *Value-Focused Thinking* (Cambridge, Massachusetts: Harvard University Press, 1992) 72.
[66] *Dictionary of Military and Associated Terms*. U.S. Department of Defense 2005. The 2010 version of this reference, Joint Publication 1-02 Department of Defense Dictionary of Military and Associated Terms, does not include a definition for the following terms: combat vehicle, fighting vehicle, or armored vehicle.
[67] Christopher F. Foss, *Jane's Armor and Artillery*, 2006-2007 (Alexandria, Virginia: Cambridge University Press, 2006). Jane's Information Group is recognized as the world leader in military reference materials.
[68] R.M. Ogorkiewicz, Design and Development of Fighting Vehicles (New York: Doubleday, 1968).

commensurate with fielded IFVs. In other words, the expansive list of ground combat vehicles requirements implies it must do it all (protect, shoot, and move).

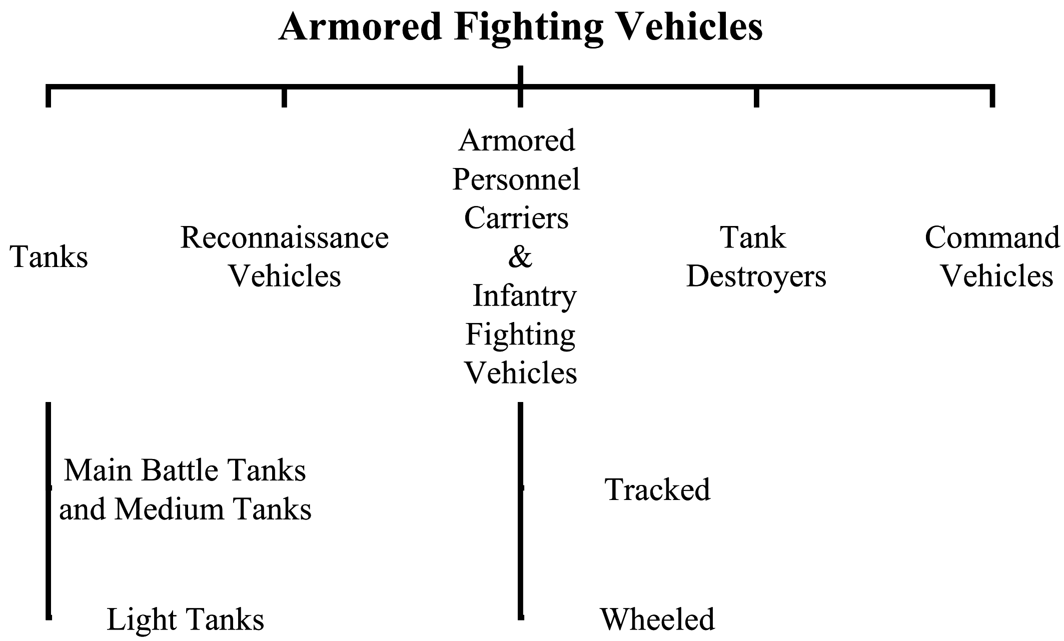

Figure 12: Five fighting vehicle categories as organized by *Jane's Armour and Artillery*.[69]

To aid in a contextual understanding of what type of performance requirements one should expect in a fighting vehicle, the technical specifications for two fielded IFVs were reviewed (Table 6). The specific requirements for the U.S. Army's current (as of the publication of this manuscript) GCV program remain under review, and, as such, the final specifications for the future GCV program will deviate from these values. The program has publicly stated that in order to achieve the required survivability performance, gross vehicle weight could extend into the 50 ton (45,000 kg) range. Mobility requirements have been informally described as at the level currently (again, as of the publication of

[69] Christopher F. Foss, *Jane's Armor and Artillery*, 2006-2007 (Alexandria, Virginia: Cambridge University Press, 2006).

this manuscript) attained by the M2 Bradley. However, for a general understanding of mission profile and system function, these fielded system specifications were considered to be within an acceptable range of the performance requirements one should expect from the next generation IFV in the GCV program. For visual reference, a drawing of a commercial GCV concept presented in 2010 is provided in Figure 13.

Table 6: Performance Specifications for the M2 Bradley and BMP-3 Kurgan IFVs[70]

Variant ► (Country) ► Specifications ▼	**M2 Bradley (U.S.)**	**BMP-3 Kurgan (Russia)**
Gross Vehicle Weight [tonne]	27.6	18.7
Crew / Dismounts	3/6	3/7
Protection [mm armor]	≈ 30 (all around)	≈ 30 (frontal)
Armament	25 mm Bushmaster TOW missile	30 mm 2A72 100 mm cannon
Top Speed [km/hr]	66	72
Range [km]	483	600
Power to Weight [kw/tonne]	16.2	20.1

[70] Foss, Christopher F. *Jane's Armor and Artillery, 2006-2007*. (Virginia: Cambridge University Press, 2006). These performance specifications are for currently fielded systems.

Figure 13: Concept image of the BAE submission for the GCV (source, BAE 2010).

2.2.3 Full Spectrum Operations

With a working description for the ground combat vehicle and some representative examples of currently fielded systems, the next step was identification of the role this platform fills in the maneuver brigades that fight them in combat. The U.S. Army Field Manual (FM) 3-0 *Army Operations* states the goal of full spectrum operations in the following way:

> The goal of full spectrum operations is to apply landpower as part of unified action to defeat the enemy on land and establish the conditions that achieve the joint force commander's end state. The complexity of today's operational environments requires commanders to combine offensive, defensive, stability, and civil support tasks to do this.

The last sentence of this passage lists the four main types of full spectrum operations: offensive, defensive, stability, and civil support operations (Figure 14). Graphically, these are presented as quadrants in the continuum of full spectrum operations. Looking at the four quadrants, it appears that fighting vehicles, particularly GCV type platforms, will continue to play a major role in accomplishing the primary tasks listed for offensive, defensive, and stability operations.[71]

For offensive operations, fighting vehicles remain crucial components in completing tasks such as movement to contact, attacks, exploitation, and pursuits. For defensive operations, combat vehicles enable commanders to conduct mobile defense, area defense, and retrograde tasks. In support of stability operations, combat vehicles can enhance the establishment and enforcement of civil security and civil control, the baseline requisites for other tasks such as restoration of essential services and support to local governance.

[71] U.S. Army Field Manual 3-0, *Army Operations*, Headquarters, Department of the Army, Washington, D.C., 2008, 3-7.

<table>
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Offensive Operations

Primary Tasks
- Movement to contact
- Attack
- Exploitation
- Pursuit

Purposes
- Dislocate, isolate, disrupt, and destroy enemy forces
- Seize key terrain
- Deprive the enemy of resources
- Develop intelligence
- Deceive and divert the enemy
- Create a secure environment for stability operations

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Defensive Operations

Primary Tasks
- Mobile defense
- Area defense
- Retrograde

Purposes
- Deter or defeat enemy offensive operations
- Gain time
- Achieve economy of force
- Retain key terrain
- Protect the populace, critical assets, and infrastructure
- Develop intelligence

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Stability Operations

Primary Tasks
- Civil security
- Civil control
- Restore essential services
- Support to governance
- Support to economic and infrastructure development

Purposes
- Provide a secure environment
- Secure land areas
- Meet the critical needs of the populace
- Gain support for host-nation government
- Shape the environment for interagency and host-nation success

</td>
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Civil Support Operations

Primary Tasks
- Provide support in response to disaster or terrorist attack
- Support civil law enforcement
- Provide other support as required

Purposes
- Save lives
- Restore essential services
- Maintain or restore law and order
- Protect infrastructure and property
- Maintain or restore local government
- Shape the environment for interagency success

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Figure 14: Four quadrants of full spectrum operations for the U.S. Army, including offensive, defensive, stability, and civil support operations (from U.S. Army Field Manual 3-0, *Army Operations*).

The physical movement afforded by these platforms, combined with the firepower delivered with the weapons they possess, join to form a vital capacity called *maneuver*. Maneuver is defined as the employment of forces in battlespace to achieve a position of advantage in respect to the enemy in order to accomplish the mission.[72] As a military term, *maneuver* also serves as a principle of war. Moreover, fighting vehicles are the U.S. Army's foundation for effective and decisive maneuver warfare in the prosecution of major combat operations (offense and defense) within full spectrum operations.

[72] U.S. Army Field Manual 1-02, *Operational Terms and Graphics*, Headquarters, Department of the Army, Washington, D.C., 2006, 1-117.

When reviewing the balance between participation in major combat versus stability operations, "contrary to popular belief, the military history of the United States is one characterized by stability operations, interrupted by distinct episodes of major combat."[73] Since its inception over two centuries ago, the U.S. Army has fought in 11 wars, but participated in hundreds, if not thousands, of operations that can be classified as stability operations, such as *Joint Endeavor* (Bosnia) in 1995 and *Restore Hope* (Somalia) in 1992. In contrast to these examples of stability operations, the major combat operations comprising wars were "the wars for which the military traditionally prepared; these were the wars that endangered America's very way of life."[74] Looking forward, if history is any guide, it is likely that the demands and requirements for the U.S. Army will revolve around the preparation for and execution of stability operations (most likely course of action). However, the greatest risks to both national security and national interest may focus around the challenges associated with facing a peer threat in a future war (most dangerous course of action). Generating requirements and developing materiel solutions that consider both the most likely and most dangerous course of action for future forces is paramount to properly equipping future forces.

The concept of full spectrum operations can be overlaid atop the previously presented spectrum of puzzles and mysteries. In accordance with U.S. Army Field Manual 3-0, each of the components of full spectrum operations is a composite of subjective fractions of offensive, defensive, and stability operations. If the prosecution of major combat operations (offensive and defensive) is characterized primarily by puzzles, and if the conduct of stability operations is characterized primarily by mysteries, then full spectrum operations can be viewed as a continuous region on an *x-y* plot, with puzzle and

[73] U.S. Army Field Manual 3-07, *Stability Operations,* Headquarters, Department of the Army, Washington, D.C., 2008, paragraphs 1–1 through 1–9.
[74] Ibid.

mystery as the x- and y-axes respectively (Figure 15). Note that civil support operations are not included in this figure as this is a purely domestic role for the military.

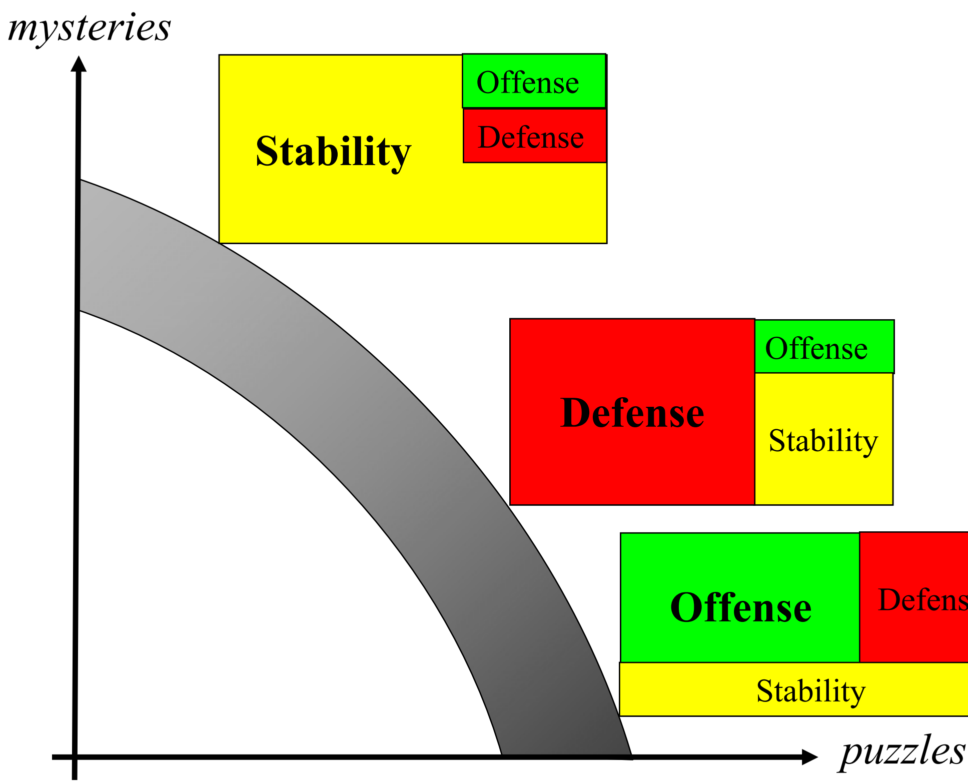


Figure 15: Full spectrum operations depicted as a continuum in the puzzle-mystery space. (Representative blocks for Offense, Defense, and Stability operations are based on depictions from U.S. Army Field Manual 3-0, *Army Operations*.)[75]

The representative blocks in Figure 15 mesh with the notion of full spectrum operations in that each major type of operations, i.e., offensive, defensive, or stability, is a composite of all three. This is true in a static sense or from a point of departure for an operation. Dynamically, operations evolve over time and can shift quite rapidly from one focused type to another. At the tactical level, U.S. Marine Corps General Charles C.

[75] U.S. Army Field Manual 3-0, *Army Operations*, Headquarters, Department of the Army, Washington, D.C., 2008, 3-1.

Krulak famously coined the term *three block war* to describe how a small unit operating in a city could simultaneously be battling an insurgent force, conducting stability operations, and defending against an attack.[76] Krulak's article dealt mostly with the requirements of contemporary, small-unit leaders, i.e., that they must be prepared to operate with agility in light of the rapid transitions that can take place on the modern battlefield. That said, the points made in his article reinforce the notion of a continuum for full spectrum operations. The concept of a three block war also illustrates the dynamic and transitive nature of modern warfare, and the inherent necessity that the warfighter be equipped with an array of hardware that can contribute toward success across the entire spectrum of operations.

2.2.4 The Eight Elements of Combat Power

When considering the U.S. Army's eight elements of combat power (Figure 16), the recognized value of a fighting vehicle possessing some level of battlefield survivability, lethality, and mobility translates directly to three elements of combat power, namely, the protection, fires, and movement/maneuver terms. As mobile and armored information hub or node, the combat vehicle can also enable the command and control and intelligence elements. Finally, a combat vehicle can serve as a modern-day mule, carrying provisions (food, water, ammunition, supplies) far exceeding what any individual can carry into battle.

[76] Charles Krulak, "The Strategic Corporal: Leadership in the Three Block War," Marine Corps Gazette Vol. 83, Issue 1 (January 1999), 18-23.

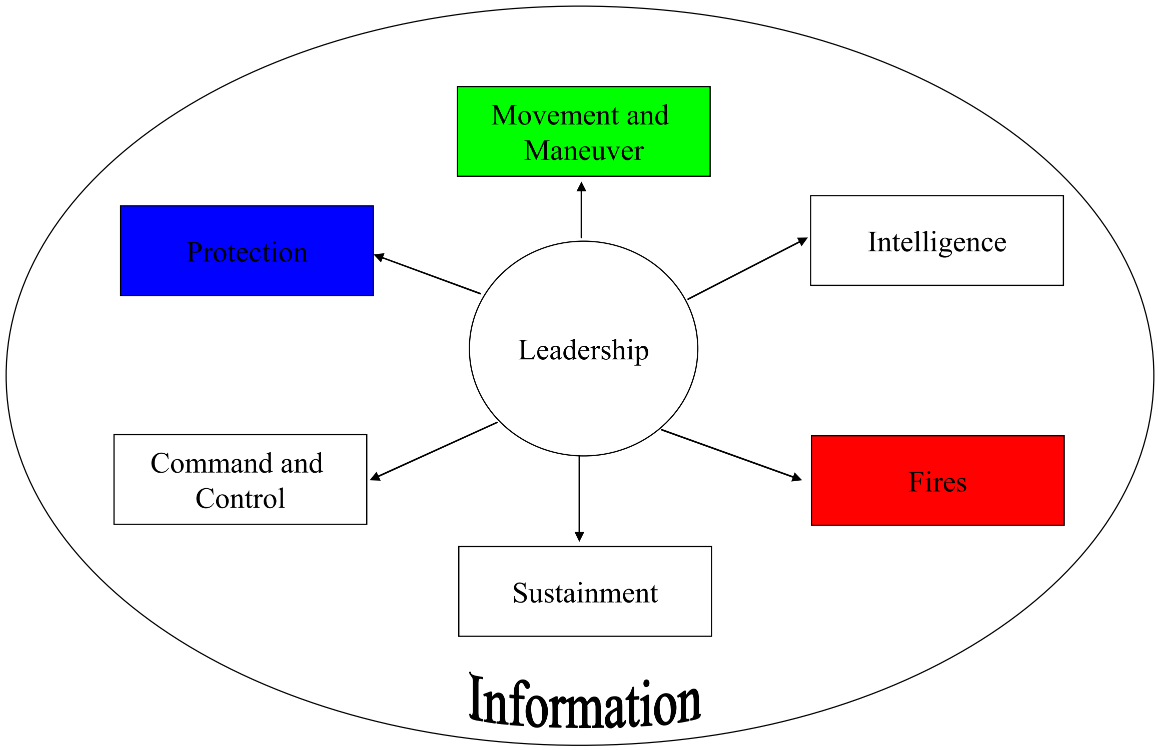


Figure 16: Eight elements of combat power (based on figure from U.S. Army Field Manual 3-0, *Army Operations*). Note that leadership resides at the hub of employing these elements, and all elements are further enabled by a network that provides timely and accurate information to commanders. As stated in U.S. Army Field Manual 3-0, *Army Operations*, "leadership and information are applied through, and multiply the effects of, the other six elements of combat power." The element of protection is shaded blue, denoting its relationship to survivability. Fires and movement are shaded red and green, respectively, to signify their affinity with lethality and mobility. Intelligence, command and control, and sustainment are not shaded, but the subjective contributions of a combat vehicle toward these elements was mentioned previously.[77]

U.S. Army Field Manual 3-0 defines combat power as the "total means of destructive, constructive, and information capabilities that a military unit/formation can

[77] U.S. Army Field Manual 3-0, *Army Operations*, Headquarters, Department of the Army, Washington, D.C., 2008, 4-1.

apply at a given time."[78] U.S. Army forces generate combat power by converting potential into effective action.[79] In providing capabilities specified by these aforementioned primary tasks in full spectrum operations, and by directly complementing three elements of combat power, ground combat vehicles fulfill a vital role for forces conducting full spectrum operations.

2.2.5 Principles of War

A final doctrinal consideration that aided in establishing the foundational basis for combat vehicle design was a review of the U.S. Army's principles of war. Based largely on the work of Prussian military theorist Carl von Clausewitz in the 1800s, and first published by the U.S. Army after World War I, these principles are the enduring bedrock of U.S. Army doctrine.[80] The principles of war summarize the characteristics of successful operations; remaining mindful of them can help reinforce those aspects of materiel pursuits in harmony with these principles.

When considering the principles of war, the broad applicability of a mobile, protected, weapon system is directly applicable to six (highlighted in Table 7) of these nine principles. If the ultimate objective is to destroy an enemy's ability (or will) to fight, then projecting combat power via a fighting vehicle is an asset to conducting operations. For offensive actions, the speed and firepower provided by these systems yields superior maneuver capability that can be employed to put the enemy at a position of disadvantage. This capacity also lends itself to massing of weapon system effects on the enemy. Finally, the protection afforded by a ground combat system can enhance both local and platform

[78] U.S. Army Field Manual 3-0, *Army Operations*, Headquarters, Department of the Army, Washington, D.C., 2008, 4-1.
[79] Ibid.
[80] Ibid., paragraphs 4-11 through 4-15.

security, while the mobility and firepower create opportunities for surprise, which can be generated by moving faster across terrain that is seemingly impassible.

Table 7: U.S. Army Principles of War [81]

Principle	**Short Definition**
Objective	Direct every military operation toward a clearly defined, decisive, and attainable objective.
Offensive	Seize, retain, and exploit the initiative.
Mass	Concentrate the effects of combat power at the decisive place and time.
Economy of Force	Allocate minimum essential combat power to secondary efforts.
Maneuver	Place the enemy in a disadvantageous position through the flexible application of combat power.
Unity of Command	For every objective, ensure unity of effort under one responsible commander.
Security	Never permit the enemy to acquire an unexpected advantage.
Surprise	Strike the enemy at a time or place or in a manner for which he is unprepared.
Simplicity	Prepare clear, uncomplicated plans and clear, concise orders to ensure thorough understanding.

Before decomposing the combat vehicle performance into the principal attributes, secondary traits, and tertiary (engineering) metrics that directly contribute to the successful generation of combat power, it was necessary to first examine the stratified configuration of the military organization, also known as the "levels of war".[82]

[81] U.S. Army Field Manual 3-0, *Army Operations*, Headquarters, Department of the Army, Washington, D.C., 2008, paragraphs 4-11 through 4-15.
[82] Ibid., paragraphs 6-1 through 6-4.

2.3 Tactical, Operational, and Strategic Levels of War

With over 1.5 million service members, a similar number of government civilians and contractors, and a 2010 operating budget of over $500 billion, the U.S. DoD represents one of the largest bureaucracies on earth. The established levels of war define the coarse framework for the hierarchical structure that exists in both U.S. DoD and the U.S. Department of the Army. The levels of war clarify the relationship between strategic decisions, operational approach, and tactical actions.[83] There is a perhaps necessarily contentious relationship between the various levels of war, best captured with the following quote from U.S. Army Field Manual 3-0.

> A natural tension exists between the levels of war and echelons of command. This tension stems from different perspectives, requirements, and constraints associated with command at each level of war. [84]

Figure 17 depicts the three levels of war with their respective areas of emphasis listed to their right. From the commercial materiel enterprise perspective, the tactical level of war equates to the customer or end user at the retail level. The operational level can be likened to the distribution network connecting the wholesale to the retail level. The strategic is akin to the highest level of corporate management and leadership, where production and manufacturing might occur; this level also controls the conversion of resources, along with the introduction of assets into the "exchange process". It may be interesting to note that the gross generalizations presented for the focus of each level does not explicitly include mention of survivability.

[83] U.S. Army Field Manual 3-0, *Army Operations*, Headquarters, Department of the Army, Washington, D.C., 2008, paragraphs 7-1 through 7-4.
[84] Ibid.

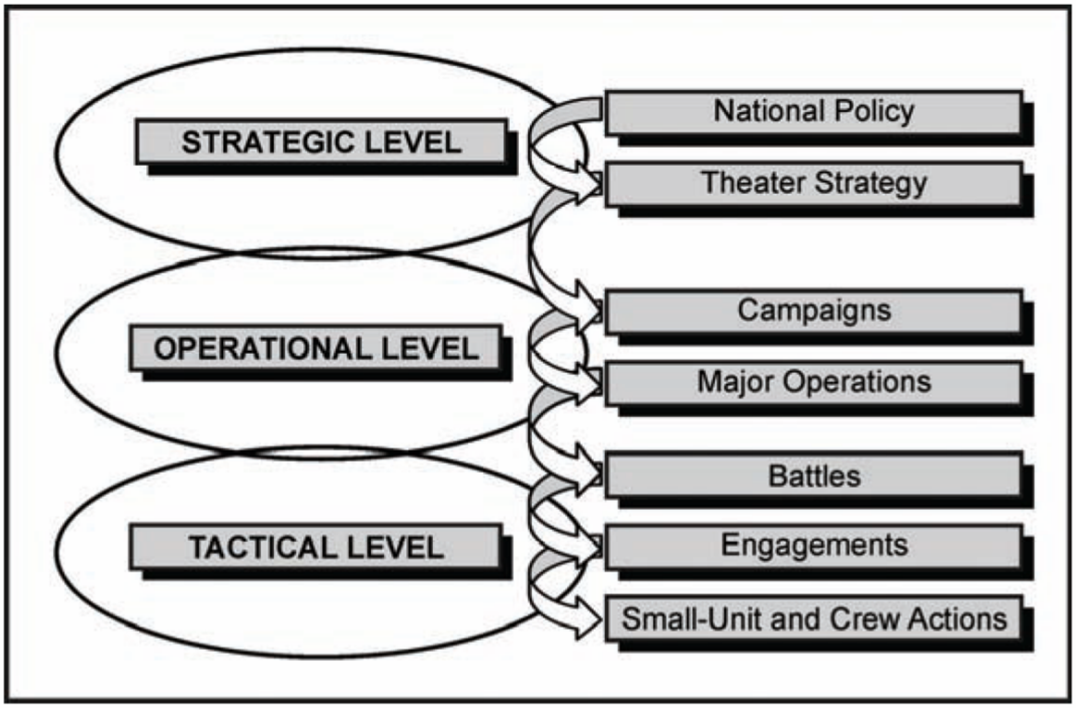


Figure 17: Three levels of war with highlighted areas of responsibility.[85]

This exchange process operates on both a "push" and "pull" system based on both anticipated requirements and stated demand. As such, it is highly coupled, and each level retains resources for discretionary use (or non-use). For example, some of the MRAPs that were expedited into the OEF theater via strategic and operational level transport units went underutilized by tactical units given their (tactical level) assessment that the size and weight of these platforms was not conducive with operations in the mountainous terrain defining much of Afghanistan.[86] In response to this, subsequent variants, which are smaller and more maneuverable, have seen greater tactical employment.

[85] Figure from U.S. Army Field Manual 3-0, *Army Operations*, Headquarters, Department of the Army, Washington, D.C., 2008, 7-2.
[86] Andrew Feickert, Specialist in Military Ground Forces, "Mine-Resistant, Ambush-Protected (MRAP) Vehicles: Background and Issues for Congress" Congressional Research Service, RS22707, January 18, 2011. This report has a dedicated section on the status of unused MRAPs in Afghanistan.

A fighting vehicle, as a pertinent and illustrative example, is employed for use at the tactical level (customer/retail), is delivered to theater and sustained there by the operational level (distribution/wholesale), and is originated into service and released for combat via the strategic level (manufacturing and production/corporate). This notion complements the military definition for combat power and the levels of war from U.S. Army Field Manual 3-0, where the conversion process through the levels is described as the transformation of "potential power into action." Take, for example, fuel used to power a combat platform. It enters the system (theater of battle) via an exchange of resources at the strategic level. The volume of fuel flows through an operational-level exchange network to the tactical level, where it is then transformed into power for the user. A more concrete demonstration of this concept can be made from Operation Desert Storm. In the six-month buildup to combat operations, tens of millions of gallons of diesel fuel was stockpiled in the vicinity of the theater of battle. Once combat operations commenced, this vast supply was distributed from the operational to the tactical level.[87]

At the macroscale, strategic interest is focused on gaining the most capability from the resources exchanged. As the end-user, the tactical level also wants the most capability. However, the tactical level, operating at the microscale of operations, understandably has less consideration for the assets involved in providing that combat power. The operational level, working in a mesoscale between the tactical and strategic levels, desires an efficient conversion at the eventual transformer, one that minimizes demands placed on the distribution network and that can be transported easily, efficiently, and effectively.

[87] William G. Pagonis, Jeffrey L. Cruikshank, *Moving Mountains: Lessons in Leadership and Logistics from the Gulf War* (Massachusetts: Harvard Business Press, 1992) 70.

One point of confusion may arise when trying to distinguish between actions and effects at a specific level versus acting at that level. FM 3-0 explains that:

> at times, their [tactical] actions may produce strategic or operational effects. However, this does not mean these elements are acting at the strategic or operational level. Actions are not strategic unless they contribute directly to achieving the strategic end state. Similarly, actions are considered operational only if they are directly related to operational movement or the sequencing of battles and engagements. The level at which an action occurs is determined by the perspective of the echelon in terms of planning, preparation, and execution.

Table 8: Levels of War with Commercial Analogues

Level of War (scale)	**Emphasis**	**Commercial Analogue**
Strategic (macroscale)	Global Resource Management	Corporate Production
Operational (mesoscale)	Theater Delivery and Sustainment	Wholesale Distribution
Tactical (microscale)	Missions and Actions	Retail Customer

The strategic level of war provides military forces and other related capabilities in accordance with strategic plans. The operational level of war links employing tactical forces to achieving the strategic end state. Actions at the operational level usually involve broader dimensions of time and space than the tactical level actions do. The tactical level focuses on the use of combat power in battles, engagements, and unit actions. Individuals, crews, and small units act at the tactical level.[88] But, these comments may

[88] U.S. Army Field Manual 3-0, *Army Operations*, Headquarters, Department of the Army, Washington, D.C., 2008, paragraphs 7-9 through 7-16.

unfairly “flatten” or oversimplify the dynamic interactions vertically between levels and horizontally at each level. For example, tactical operators clearly consider the objectives and effects of their actions on parent organizations, and operational level planners forecast needs in order to respond in an anticipatory manner to the needs of their subordinate level. However, the main focus for each level can still be generally summarized as being maximum power at the tactical level, high efficiency at the operational level, and overall effectiveness at the strategic level. While, survivability contributes to the preservation of those assets over time, the lack of mention in the generalized focus for each level is not intended to connote that the operational or strategic level is not primarily focused on protecting crewmembers, which is tacitly assumed. However, discussions dealing with strategically and operationally mobile platforms typically revolve around the benefits of rapid deployment for strike purposes; they do not highlight the secondary effects of quickly emplacing more vulnerable platforms, versus taking more time to move better protected vehicles.

2.4 Principal Attributes in the Survivability, Lethality, and Mobility Framework

With an appreciation for the competing interests at the various levels of war, recognition for the contribution ground combat vehicles can make in the execution of full spectrum operations, and the involvement of these platforms in the generation of combat power, the last step was to fully explore the ground combat vehicle principal attributes of survivability, lethality, and mobility. For the present work, this began at the tactical level of war.

As previously mentioned, fighting vehicles provide operators with a mobile and protected source of firepower that can be utilized in an array of missions including offensive, defensive, and security operations. These key and essential platform attributes are known doctrinally as survivability, lethality, and mobility. Survivability provides protection to both the crew and combat system; lethality supplies the necessary firepower to destroy or neutralize battlefield threats; and mobility yields movement and freedom to maneuver across the combat zone. These three principal attributes will later be deconstructed further into secondary traits and tertiary metrics. Figure 18 provides a graphical depiction of how a combat platform notionally presents concentrated areas for the hardware primarily associated with these principal attributes.

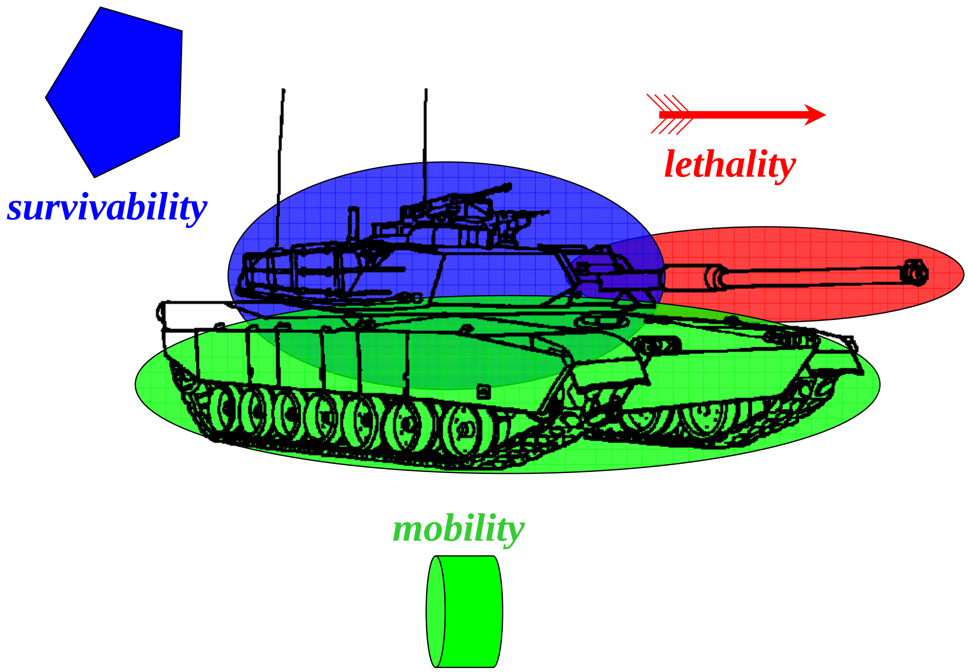


Figure 18: U.S. M1 Abrams tank with notional areas representing regions of system survivability, lethality, and mobility components. [89]

Used interchangeably with protection (survivability), firepower (lethality), and movement (mobility), survivability, lethality, and mobility were chosen because these particular attribute titles are universally recognized and fairly well defined in the literature. To establish a baseline for this taxonomy as it is used throughout this dissertation, the principal attributes were first formally defined and referenced; then, distinctions for each were made at the various levels of war. The main reference was from the previously introduced AIAA text by Deitz et al. As mentioned, this timely publication appears to be the only work solely dedicated to the topic of ground combat system survivability and lethality. In addition to the text by Deitz et al., where available, applicable, and necessary, this taxonomy was complemented with the service doctrinal

[89] Source for the unmodified U.S. M1 Abrams tank drawing is: www.olive-drab.com/images/clipart_gallery/land_m1.gif

working definitions like those found in U.S. Army Field Manuals, e.g., FM 3-0 *Operations*, FM 1-02 *Operational Terms and Graphics*, and FM 3-90 *Tactics.*

2.4.1 Survivability

The first tanks fielded during World War I spawned from a requirement to provide a protected means of navigating the no-mans land on a battlefield typified by trench warfare. The inclusion of armor protection enabled these mobile weapon platforms to traverse the non-permissive environment laying between opposing forces and their trench lines. It may, therefore, be fitting to begin deconstruction of the principal attributes with an investigation of survivability. Deitz et al. define the attribute of survivability as:

> the total capability of a system (resulting from the synergism among personnel, materiel, design, tactics, and doctrine) to avoid, withstand, or recover from damage to a system or crew in a hostile (man-made or natural) environments without suffering an abortive impairment of its ability to accomplish its designated mission.[90]

This holistic definition includes consideration for the crew as well as the platform. It is also consistent with the version provided by U.S. Army Field Manual 1-02, *Operational Terms and Graphics*. Using the tank example, survivability is passively provided by the protective armor shielding the crew and actively provided through sensing efforts, communication with others, countermeasures, evasive maneuvers initiated by crewmembers, and safety equipment, e.g., fire suppression, system monitoring, and protective devices.

[90] Deitz, Paul H., Harry L. Reed Jr., J. Terrence Klopcic, James N. Walbert. *Fundamentals of Ground Combat System Ballistic Vulnerability and Survivability* (Virginia: American Institute of Aeronautics and Astronautics, 2009) 15-18.

2.3.1.1 Survivability Secondary Traits of Vulnerability, Susceptibility, and Repairability

According to Deitz et al., ground combat system survivability is a function of its vulnerability, susceptibility, and repairability.[91]

Survivability = f(Susceptibility, Vulnerability, Repairability)

Susceptibility comprises the "characteristics of a system that make it unable to avoid being engaged by threats on the battlefield. This includes being detected, tracked, targeted, and engaged up to the point of being hit."[92]

Vulnerability refers to the "characteristics of a system that cause it to suffer degradation as a result of having been subjected to a hostile environment on the battlefield."[93] The hostile environment includes an insult, or "an external, munition-produced physical agent capable of producing injury."[94] This agent can take multiple forms, for example, incident pressure, heat flux, kinetic energy, or radiation.

Repairability is the capacity for the system to regain function following an insult. The Defense Acquisition University (DAU) glossary defines it as "the restoration or replacement of parts or components of real property or equipment as necessitated by wear and tear, damage, failure of parts or the like, in order to maintain it in efficient operating condition."[95]

[91] Deitz, Paul H., Harry L. Reed Jr., J. Terrence Klopcic, James N. Walbert. *Fundamentals of Ground Combat System Ballistic Vulnerability and Survivability* (Virginia: American Institute of Aeronautics and Astronautics, 2009) 2-9.
[92] Ibid., 2.
[93] Ibid., 2-3.
[94] Ibid., 54.
[95] Defense Acquisition Univeristy Glossary of Terms, Defense Acquisition University Press, Fort Belvoir, Virginia; available for download at: https://dap.dau.mil/glossary/Pages/Default.aspx.

Considering the notional engagement of a fighting vehicle, these traits can be presented sequentially: the susceptibility characterizes the ease of detection and subsequent insult, the vulnerability describes the reaction or effect of an insult, and the repairability portrays how quickly the system can recover. To use a boxing analogy, these three traits can be used to describe: how well one can avoid being hit (susceptibility), how much damage is done if one takes a punch (vulnerability), and how quickly one can get back to his feet after a knock-down blow (repairability).

2.3.1.2 Survivability Tertiary Metrics

With the principal attribute of survivability defined, and the three secondary traits of susceptibility, vulnerability, and repairability described, the collection of tertiary (engineering) metrics that relate to survivability were organized in a subordinate fashion. This list of metrics is obviously not all inclusive, but represents a substantial group of terms typically used to generate performance requirements or describe vehicle specifications. These tertiary metrics were organized subordinate to a relevant secondary trait. For each metric, a short definition is provided, as well as the units of measurement. Traits are presented sequentially for a notional engagement between threat and friendly vehicle, and the corresponding metrics are ordered alphabetically. Comments are provided regarding the select metrics with identified design conflict with another metric, trait, or attribute. The process of considering the contributory and conflicting effects was done in a “crosswalk” method. This means the metric was virtually walked across each other metric, trait, and attribute to subjectively assess the measured effect, either in contribution or reduction to the term of interest.

Table 9: Survivability Secondary Traits and Tertiary Metrics

ATTRIBUTE **Trait** metric	**Short Definition**	**Unit**	**Desired Trend**
SURVIVABILITY	ability to withstand hostile environment	n/a	↑
Susceptibility	prevent detection	n/a	↓
$A_{\text{presented}}$	area presented to threat	m^2	↓, ↔
envelope	volume occupied by platform	m^3	↓, ↔
e_s	ratio of target thickness along shot line	#	↓
footprint	area occupied by platform	m^2	↓, ↔
P_{ground}	ground pressure	kPa	↓
$signature_{\text{acoustic}}$	acoustic signature	dB	↓
$signature_{\text{em}}$	electromagnetic signature	T	ca B_{amb}
$signature_{\text{thermal}}$	thermal signature	K	ca T_{amb}
$signature_{\text{visual}}$	visual signature	nm	ca λ_{amb}
Vulnerability	tolerate an insult		↓
BPR	blast protection rating, yield corresponding	#	↑, ↔
$E_{\text{combustible}}$	energy yield of combustibles (fuels, propellant)	kJ	↓, ↔
e_m	areal density ratio of RHA_e and complex armor	#	↓
facet	angular orientation of exterior	°	ca 45°
mass	vehicle mass	kg	↑,↔
$m_{\text{exposed fraction}}$	mass fraction of gross vehicle weight unarmored	#	↓,↔
$P_{\text{overpressure}}$	peak overpressure in crew area	kPa	↓
$RHA_{\text{equivalent}}$	equivalent armor protection of MIL-A-12560	mm	↑
vee-hull	beneficial shape for hull for blast deflection	°	ca 45°
Repairability	recover from insult		↑
exposure	components exposed to environment	#	↓
modularity	number of main components, plug and play	#	↑
t_{repair}	time to repair or replace critical components	hr	↓

The last column indicates the notionally desired direction for utility, that is, to either increase or decrease that metric.
↑: An upward facing arrow indicates this metric should be as great as possible.
↓: A downward facing arrow indicates this metric should be as small as possible.
ca: The abbreviation “ca” stands for “centered about”, as several metrics are measured as absolutes from a desired value.
↔: The left-right arrow bar indicates there is a competition with another attribute and its traits.

2.4.2 Lethality

The potency of a combat vehicle weapon system is captured with the attribute, lethality. Deitz et al. define lethality as "the ability of a weapon system to cause the loss of, or degradation in, the ability of a target system to complete its designated mission." He goes on to explain that "often for direct fire weapons, the delivery of the threat from launch to target impact is integral to the lethality analysis." This definition is target-centric, meaning that this term is reserved or qualified for a specific threat system under specific conditions.

The firepower carried aboard a combat vehicle is the distinguishing feature that sets it apart from another type of platform colloquially referred to as a "battlefield taxi". The weapon system, and the optics that accompany it, provide the fighting vehicle with the tools necessary to identify and subsequently destroy threat targets. Euphemisms used to describe the capabilities of these weapons (target effects, destroy, attrit, etc.) are all references to the destructive power carried aboard a fighting vehicle.

Interestingly, there appears to be no doctrinal definition for lethality, despite the fact that this term is mentioned repeatedly throughout the literature as an element of combat power and is clearly an essential quality possessed by an effective fighting platform. The DAU definition is simply "the probability that a weapon will destroy or neutralize a target."[96] Again, this is a weapon and target-centric definition. More broadly, lethality is a function of the likelihood that the threat was acquired, that munitions hit the target, and that the damage incurred from the insult is debilitating enough to render incapacitation or negation of a threat. The target acquisition portion is a function of several factors, most of which deal with human performance (target identification

[96] Defense Acquisition Univeristy Glossary of Terms, Defense Acquisition University Press, Fort Belvoir, Virginia; available for download at: https://dap.dau.mil/glossary/Pages/Default.aspx.

training, level of alertness, mission readiness, weather, etc.). Again, harkening back to the tank example, the lethality can be considered as the effective firepower afforded to the crew from the cannon and adjoining weapons, fire control system, and target acquiring devices.

2.3.2.1 Lethality Secondary Traits of Acquisition, Engagement, and Effects

When discussing the attribute of lethality, it can also be broken down into three traits that follow a sequential ordering similar to that of survivability: lethality is a function of the ability to detect and acquire a threat, to engage the threat with a weapon system, and to create the desired effect on the target, that is, to induce an insult commensurate with a level of incapacitation.

$$\text{Lethality} = f\,(\text{Acquisition, Engagement, Target Effects})$$

Conventional books on weaponry typically parse lethality in terms of internal ballistics, external ballistics, and terminal ballistics.[97,98] The terminology of internal, external, and terminal ballistics is restricted to weapons that deploy a projectile of some sort. Although this is a valuable framework, this manuscript will use traits termed as acquisition, engagement, and effects to cover a broader class of weapons, while still observing a sequence corresponding to the same periods and events involved in an engagement. More specifically,

Acquisition covers the time from target acquisition to the commission of launch.

Engagement includes the time from launch to target—from muzzle to impact.

Effects covers the event from impact incidence to rest.

[97] Donald E. Carlucci, Sidney S. Jacobson, *Ballistics: Theory and Design of Guns and Ammunition* (New York: CRC Press, 2007) sections I, II and III.
[98] *Rheinmetall Handbook on Weaponry* (Düsseldorf: Rheinmetall GmbH, 1992).

In the literature, these respective traits converge to produce various probabilities associated with successful engagement of a threat. For example, a given weapon system facing a specific threat in a defined situation will have probabilities of detection P_{detect}, hitting the threat P_{hit}, damaging the threat P_{damage}, system availability $P_{\text{availability}}$, the product of these determine the probability of kill P_{kill}.[99] This kill can even be further parsed as a mobility kill, firepower kill, or catastrophic kill.[100] These probabilities combine to form a total probability of kill.

$$P_{\text{kill}} = P_{\text{detect}}P_{\text{hit}}P_{\text{damage}}P_{\text{availability}} \qquad \text{Equation 2}$$

2.3.2.2 Lethality Tertiary Metrics

In a similar fashion previously presented for survivability, the tertiary metrics corresponding to the three secondary traits for lethality, i.e., acquisition, engagement, and effects, are presented in Table 10. The same arrow convention is used throughout. Again, the metrics presented are those consistently referenced as being key and essential to the design and analysis of a weapon system.

[99] Deitz, Paul H., Harry L. Reed Jr., J. Terrence Klopcic, James N. Walbert. *Fundamentals of Ground Combat System Ballistic Vulnerability and Survivability* (Virginia: American Institute of Aeronautics and Astronautics, 2009) 64-70.
[100] Ibid.

Table 10: Lethality Secondary Traits and Tertiary Metrics

ATTRIBUTE **Trait** metric	**Short Definition**	**Unit**	**Desired Trend**
LETHALITY	ability to destroy a threat		↑
Acquisition	target detection to launch		↑
CAL	combat ammunition load	#	↑, ↔
$P_{\mathrm{detection}}$	probability of detection	%	↑
$range_{\mathrm{PID}}$	range to positively identify	[m]	↑
tuneability	ability to tune to target specificity	#	↑
Engagement	commission to target insult		↑
CEP	circular error probability	cm	↓
l_{cannon}	cannon length	m	↑, ↔
E_{muzzle}	muzzle energy	[MJ]	↑
F_{recoil}	recoil force	kN	↓
m_{launcher}	launcher mass	kg	↑, ↔
MER	maximum effective range	m	↑
P_{hit}	probability of hit	%	↑
t_{reload}	reload time	s	↓
$\eta_{\mathrm{ballistic}}$	ballistic efficiency	%	↑
$\eta_{\mathrm{parasitic}}$	parasitic mass ratio	#	↓
$\eta_{\mathrm{piezometric}}$	piezometric efficiency	%	↑
Target Effects	terminal ballistic event		↑
BAD	behind-armor debris	N·s	↑
$d_{\mathrm{penetration}}$	penetration channel diameter	mm	↑
E_{residual}	residual energy after penetration	kJ	↑
E_{target}	energy imparted to target	[MJ]	↑
KE	kinetic energy on target	kJ	↑
P_{kill}	probability of kill	%	↑
P/L	ratio of penetration to penetrator length	#	↑
t_{flight}	flight time	s	↓
V_{crater}	crater volume induced into target	cm^3	↑

The last column indicates the notionally desired direction for utility, that is, to either increase or decrease that metric.
↑: An upward facing arrow indicates this metric should be as great as possible.
↓: A downward facing arrow indicates this metric should be as small as possible.
ca: The abbreviation “ca” stands for “centered about”, as several metrics are measured as absolutes from a desired value.
↔: The left-right arrow bar indicates there is a competition with another attribute and its traits.

2.3.3 Mobility

When considering the attribute of mobility, U.S. Army Field Manual 101-5-1 *Operational Terms and Graphics* defines it as "a quality or capability of military forces which permits them to move from place to place while retaining the ability to fulfill their primary mission."[101] Those activities enable a force to move personnel and equipment on the battlefield without delays due to terrain or obstacles. One can consider the functional rolling chassis of a notional fighting vehicle as providing the system with its inherent mobility. Bekker, a pioneer in military mobility research who reviewed over one hundred papers, observed that "each containing a different idea of the meaning of mobility."[102] He even went so far as to suggest the word be struck from the engineering dictionary due to the inconsistency in meaning.[103] Bekker later relented and classified two separate mobilities: one describing the delivery of the system to the point of use, and the other "limited to the manifestation of mechanical interaction between the terrain and the vehicle, and between the components of the vehicle itself."[104]

In his text on the theory of ground vehicles, Wong offers a more detailed definition in the following way. "Mobility in the broad sense refers to the performance of the vehicle in relation to soft terrain, obstacle negotiation and avoidance, ride quality over rough terrain, and water crossing."[105] Absent from his definition is mention of performance on improved surfaces or roads. Since all combat vehicles will, at some time, be required to navigate this type of terrain, consideration for roadworthiness was included as a trait in the following section regarding mobility.

[101] U.S. Army Field Manual 101-5-1, *Operational Terms and Graphics*, Headquarters, Department of the Army, Washington, D.C., 2004, 1-127.
[102] Mieczyslaw Gregory Bekker, *Introduction to Terrain-Vehicle Systems.* (Ann Arbor, Michigan: University of Michigan Press, 1969), 765-767.
[103] Ibid., 768.
[104] Ibid.
[105] J.Y. Wong, *Theory of Ground Vehicles, Third Edition* (Wiley, New York: 2001) 295.

2.3.3.1 Mobility Secondary Traits of Roadworthiness, Cross Country Movement, and Robustness

Mobility is an attribute expressed by the ability to navigate three types of terrain: improved surfaces or roads, unimproved surfaces like cross-country movement, and miscellaneous obstacles.[106] Military vehicles are often required to traverse manmade and natural obstacles like horizontal gaps, vertical climbs, and water. The vehicle's robustness gives it the ability to overcome these intermittent, but show-stopping obstacles that may be encountered during an excursion.

2.3.3.2 Mobility Tertiary Metrics

In similar fashion to survivability and lethality, the tertiary metrics related to mobility are presented in Table 11. These metrics share commonality with many used within the automotive industry.

[106] Mieczyslaw Gregory Bekker, *Introduction to Terrain-Vehicle Systems.* (Ann Arbor, Michigan: University of Michigan Press, 1969).

Table 11: Mobility Secondary Traits and Tertiary Metrics

ATTRIBUTE Trait metric	Short Definition	Unit	Desired Trend
MOBILITY	movement IOT complete mission		↑
Prepared Surface	movement on roads		↑
a	acceleration	s	↓
$-a$	deceleration, stopping	s	↓
d_{stop}	stopping distance	m	↓
h	vehicle height	m	↓
l	vehicle length	m	↓
m	vehicle mass	kg	↓, ↔
range	operating range	km	↑
r_{turn}	turning radius	m	↓
r_{turret}	turret radius	m	↓
V	vehicle volume, external	m^3	↓, ↔
v_{peak}	velocity, top speed	km/hr	↑
w	vehicle width	m	↓
η_{fuel}	fuel efficiency	km/l	↑
Cross Country	movement off roads		↑
P_{ground}	ground pressure	kPa	↓
P/w	power to weight ratio	kW/kg	↑
VCI_n	vehicle cone index	#	↑
$\%slope_{climb}$	maximum slope climbing	%	↑, ↔
$\%slope_{side}$	maximum side slope movement	%	↑, ↔
Robustness	miscellaneous movement abilities		↑
$cost_{hotel}$	stationary consumption rates for fuel	l/hr	↓
fordability	ability to ford water, snorkel	m	↑
h_{climb}	vertical obstacle climbing ability	m	↑
MTBF	mean time between failure	hr	↑
OR	operational readiness rate	%	↑
$soil_{sensitivity}$	sensitivity to soil types	#	↑
$T_{sensitivity}$	sensitivity to temperature	T_{max}, T_{min}	↑
w_{gap}	gap crossing width	m	↑

The last column indicates the notionally desired direction for utility, that is, to either increase or decrease that metric.
↑: An upward facing arrow indicates this metric should be as great as possible.
↓: A downward facing arrow indicates this metric should be as small as possible.
ca: The abbreviation “ca” stands for “centered about”, as several metrics are measured as absolutes from a desired value.
↔: The left-right arrow bar indicates there is a competition with another attribute and its traits.

2.3.4 Competing Demands Among Tertiary Metrics

In designing a ground combat vehicle, there is invariably competition between these metrics, traits, and attributes. Survivability has at least seven identified metrics that compete with other traits and attributes. The area presented to the target ($A_{\text{presented}}$) should be as small as possible to minimize susceptibility, but this works against lethality in that it limits the weapon system and ammunition that can be carried. For the same reasons, while the envelope and footprint should be as small as possible to reduce exposure, this is counterproductive to designing a lethal, mobile platform as it increases the ground pressure and vehicle cone index for the same powertrain and weapon system mass. Susceptibility as a trait is also not conducive with several metrics for vulnerability. For example, when evaluating the vulnerability metrics, the blast protection rating (*BPR*) should be as high as possible to safeguard the crew from possible IED strikes. However, a high *BPR* works against traits of mobility, since the elevated weight and severe faceting of the vehicle exterior limit both on- and off-road mobility, as well as make achieving robust metrics like the vertical climbing height (h_{climb}) and maximum width gap that can be traversed (w_{gap}) more problematic.

2.3.4.1 Survivability

A survivable platform should also have the smallest amount of combustible material on board as possible. A low amount of $E_{\text{combustible}}$ reduces the risk of sympathetic detonation or deflagration of these materials in the event of insult. However, traditionally this works against lethality and mobility in that it reduces the amount of ammunition or the combat ammunition load (*CAL*) as well as the driving range of the platform. Finally, it is generally desirable to reduce the vulnerability by limiting the amount of material not under armor ($m_{\text{exposed fraction}}$). This increases the hull mass, while also constraining the exoskeletal design configuration.

With conventional technology and materials, platforms that are designed to be less susceptible tend to be more vulnerable. For example, in the military aircraft regime, this can be observed with the relative fragility of a stealth aircraft. A vehicle that has a low vulnerability is often very susceptible to detection and more likely to be subjected to insult. At a platform level, these traits are traded off against each other in an effort to obtain a desirable level of survivability performance. However, it is valuable to consider the sequence of events leading to insult, i.e. a susceptible platform can lead to insult and a test of vulnerability. For this reason, concerted efforts are being made to provide both traits in a complementary fashion, e.g., virtual cloaking technology layered atop advanced composite armors.[107]

2.3.4.2 Lethality

While the pursuit of high lethality is clearly challenging, very few metrics associated with increased lethality were found to subjectively contribute negatively to other traits or attributes, aside from its contribution to the overall mass contribution. Notable exceptions are combat ammunition load, cannon length, and weapon system mass. As previously stated, high *CAL* generally renders the vehicle less survivable. To achieve high muzzle velocity and acceptable accuracy, a long cannon (l_{cannon}) is desired, but this limits mobility, especially in constricted terrain such as an urban area. Finally, if one desires a large amount of launch energy in the weapon system, the launcher mass (m_{launcher}) must be increased, which also penalizes mobility traits. In general, nearly any

[107] For a brief explanation on the science behind active camoflauge or cloaking technologies, to include metamaterials, see http://science.howstuffworks.com/invisibility-cloak.htm.

beneficial pursuit of a metric falling beneath survivability, lethality, and mobility will incur some form of a mass and cost penalty to the platform as a whole.

2.3.4.3 Mobility

At least four metrics under mobility, namely mass, volume, vertical slope and side slope, appeared to work against other attributes. To reduce encountering restrictions, e.g., bridges, tight turns, route constrictions, the vehicle characteristics, mass and volume, are desired to be as small as possible, but this works against the design space for both survivability and lethality. The ability to climb and traverse severe slopes ($\%slope_{\text{climb}}$ and $\%slope_{\text{side}}$) should be as great as possible. Vehicles capable of this generally have a low center of gravity and high power-to-weight ratio. Further, a low center of gravity translates to reduced ground clearance, reducing the *BPR* and often increasing the width and wheelbase of the vehicle in order to maintain rollover resistance and stability.[108]

2.3.5 Tactical Principal Attribute Hierarchy

Using Saaty's Analytic Hierarchy Process (AHP) for a decision analysis framework, each of the three principal attributes at the tactical level was deconstructed into secondary traits and tertiary metrics.[109] Figure 19 contains a diagram displaying the principal attributes at the tactical level expanded down to their secondary traits. The tertiary metrics were previously presented in tabular form in subordinate classification beneath respective traits.

[108] Several methods exist to test the vehicle rollover stability, to include the tilt table, rotating table, and strap-pull techniques. Many MRAP variants, given their elevated chassis and high center of gravity, have been susceptible to rollover. In light of this risk, in September of 2010 the Marine Corps opened a solicitation (M6785410R5001) for an MRAP rollover warning device.

[109] This general technique is illustrated in James S. Dyer, Thomas Edmunds, John C. Butler, and Jianmin Jia, "A Multiattribute Utility Analysis of Alternatives for the Disposition of Surplus Weapons-Grade Plutonium" *Operations Research*, Volume 46, No 6, December 1998, 749-762.

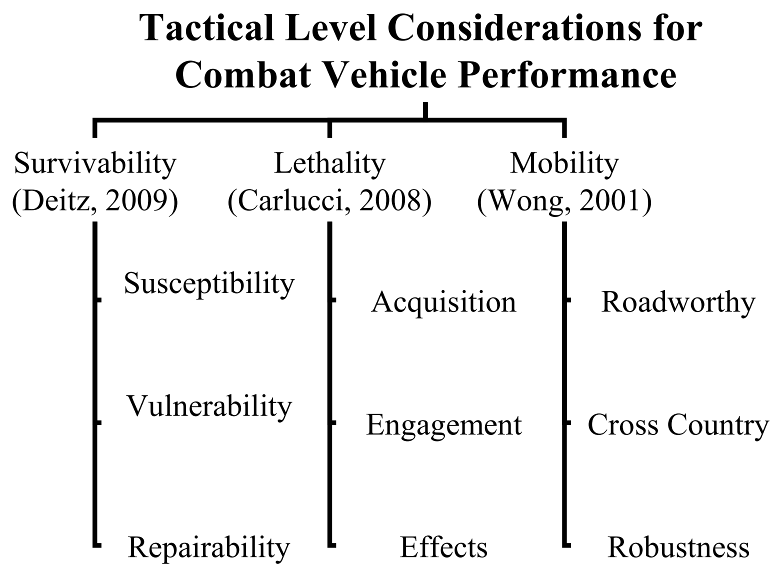


Figure 19: Hierarchy for tactical level considerations for combat vehicle principal attributes and secondary traits.

2.3.6 Operational and Strategic Principal Attribute Considerations

With the exception of those related to mobility, doctrinal and literature definitions of the principal attributes at the operational and strategic levels are not available. Notably the literature and doctrinal definitions for the three principal attributes previously presented are for the tactical level. Mobility is defined at the operational and strategic level as the transportability of the systems intra and intertheater, respectively.[110] That said, during transport, mobility is assumed to be for a mission-capable, but not mission-ready, vehicle. For example, a vehicle may require prior disembarking of the crew, external provisions, and interior preparations to conduct an intratheater movement.

[110] R.M. Ogorkiewicz, *Technology of Tanks* (United Kingdom: Jane's Information Group, 1991) 223-227.

The concepts of survivability and lethality for a tactical asset like a GCV are currently undefined at the operational and strategic levels of war. With respect to lethality, the operational level is required to support the ammunition requirements of the tactical assets within their domain. At the command of tactical leaders, the combat platforms transform the potential energy, transported through the system, and deliver it in different forms of combat power. As such, a platform that can sustain itself for long periods of time and a weapon system having a compact, efficient ammunition, necessarily places a smaller load on the operational lethality channels. In this context, operational lethality is enhanced by ground combat systems with relatively high ammunition densities, due to both large storage magazines and lighter transport requirements through the operational network. Likewise, a platform that presents high armor density normal to the threat is advantageous from an operational survivability perspective. Such vehicles are spatially efficient, providing greater protection for the same projected area, volume, or mass.

Along a similar line of logic, a given platform will have relatively high strategic lethality if the ratio of weapon caliber to vehicle height is high. Muzzle energy for conventional weapons scales with the bore diameter; a vehicle with a high ratio of bore-to-vehicle height packs more weapon energy into the confined volume of a combat platform. From a strategic lethality consideration, this means that deployed systems bring more weapon to bear on threat systems. With respect to strategic survivability, the vehicle mass density (gross vehicle weight divided by its volumetric dimensions) can serve as a first-order approximation for protection afforded to the crew. This is based on the premise that vehicle vulnerability reduces with mass, or that the protection afforded to the crew is a strong function of increased weight. Since intertheater lift capacity is limited by volume as well as mass, a system with high overall mass density provides a more efficient protection capacity to the crews. Table 12 summarizes the main sources of the definitions for the principal attributes at the three levels of war. It also depicts a labeling convention where the principal attribute is a capital letter and the level of war is a subscript letter, e.g. S_T is tactical level survivability. This convention is subsequently used in two preliminary exercises intended to further explore the concept of survivability, lethality, and mobility at the tactical, operational, and strategic levels of war.

Table 12: Principal Attribute Nomenclature and Definition Sources at the Levels of War

Principal Attribute / **Level of War**	**Survivability** [reference]	**Lethality** [reference]	**Mobility** [reference]
Strategic	$\mathbf{S_S}$ [*undefined*]	$\mathbf{L_S}$ [*undefined*]	$\mathbf{M_S}$ [Ogorkiewicz]
Operational	$\mathbf{S_O}$ [*undefined*]	$\mathbf{L_O}$ [*undefined*]	$\mathbf{M_O}$ [Ogorkiewicz]
Tactical	$\mathbf{S_T}$ [Deitz]	$\mathbf{L_T}$ [Carlucci]	$\mathbf{M_T}$ [Wong]

It may simply be that these four concepts—operational survivability (S_O), operational lethality (L_O), strategic survivability (S_S), strategic lethality (L_S)—are not definable for a tactical asset. On the topic of problematic classifications, Carol Cleland, who has studied the history and philosophy of science, commented that "people tend to make definitions when they lack theories and they want to understand something."[111] She offered additional guidance, stating that "you've got to start with the right concepts in order to formulate theories."[112] As others have observed, for terms such as these, one may only be able to, at best, "describe their characteristics, state how they act, and express their relation to other ideas, but when it comes to saying what they are, we [may have to] resort to vague generalities."[113]

[111] Clara Moskowitz, "Life's Great Mystery: What, Exactly, Is Life?" *Live Science* (December 2010) www.livescience.com/10862-life-great-mystery.htm.
[112] Ibid.
[113] Ronald L. Panton, *Incompressible Flow, Third edition* (New York, Wiley: 2006) 3-6. This quote comes from a section clarifying the differences between fundamental concepts, definitions, and laws. He later makes the analogy between words and their definitions, in that we use generally known and established terms to define less familiar words.

2.4 Exploratory Exercises for Principal Attributes at the Levels of War

Having formed the basis and initial framework for parsing a ground combat vehicle among the principal attributes of survivability, lethality, and mobility at the tactical, operational, and strategic levels of war (§ 2.3.5 and § 2.3.6), two thought experiments (sometimes referred to by the German name, *gedankenexperiment*) were conducted as a means of demonstrating the competing demands and complementary relationships among the three principal attributes throughout the three levels of war described in doctrine.

The first exercise (§ 2.4.1) was a scaling experiment in which the dimensions of mass, length, and time were explored for each attribute at each level. The purpose of this analysis was to survey and quantify the disparity in scale between each level with regards to the principal attributes.

The second exercise (§ 2.4.2) involved the ranking of eight fielded systems among the principal attributes at each level of war. The intent of this ranking examination was to populate the top portion of a quality function deployment (QFD) matrix in order to analyze the complementary and competing relationships between principal attributes at the various levels of war. The top portion or "roof" of the QFD is used to illustrate competing and complementary relationships between engineering requirements. Using the attributes as surrogate requirements, the purpose of this second exercise was to explore the synergistic, as well as conflicting, associations between attributes.

2.4.1 Exercise I: Mass, Length, and Time Scaling of Survivability, Lethality, and Mobility at the Tactical, Operational, and Strategic Levels of War

As briefly discussed, there are inherent differences in the objectives and pursuits of the tactical, operational, and strategic levels of war. While all three may share a common overarching objective, the means and motives employed at each echelon can present distinct differences in approach. The goal of Exercise I was to investigate these observed inherent conflicts in a measurable way. The approach taken in Exercise I was to quantify the approximate mass, length, and time scales between the principal attributes at the levels of war to determine whether there is an observable level of disproportion in these scales. This dimensional scaling experiment regarding the ground combat vehicle may aid in organizing the ranges of mass, length, and time associated with all three attributes at the levels of war. These ranges consider a nominal minimum and maximum estimated value required to generate and sustain that attribute in full spectrum operations in the idealized scenario below

A ground combat vehicle is deployed strategically and emplaced operationally in a tactical mission environment (Figure 20). In the conduct of a prescribed mission, this combat vehicle encounters a threat. An arbitrary region is assumed with a control surface extending around the geographical areas for each echelon.[114] The overlap of these regions serves as the exchange points between the levels of war as this tactical asset moves between inter and intratheater.

In establishing the ranges of mass, length, and time associated with the principal attributes, both the potential success and possible failure of the platform in this simple engagement is considered. A success or failure will require an amount of energy to be used for an effect related to the platform survivability, lethality, and mobility. As such,

[114] Ronald L. Panton, *Incompressible Flow, Third edition* (New York, Wiley: 2006) 5-9. Panton describes the concepts of control surfaces and control regions in this section of his text.

the conditions and associated mass, length, and time scales for success and failure are with respect to each attribute. For example, an inability to traverse terrain is regarded as a mobility failure, and an enemy vehicle left undestroyed is treated as a lethality failure.

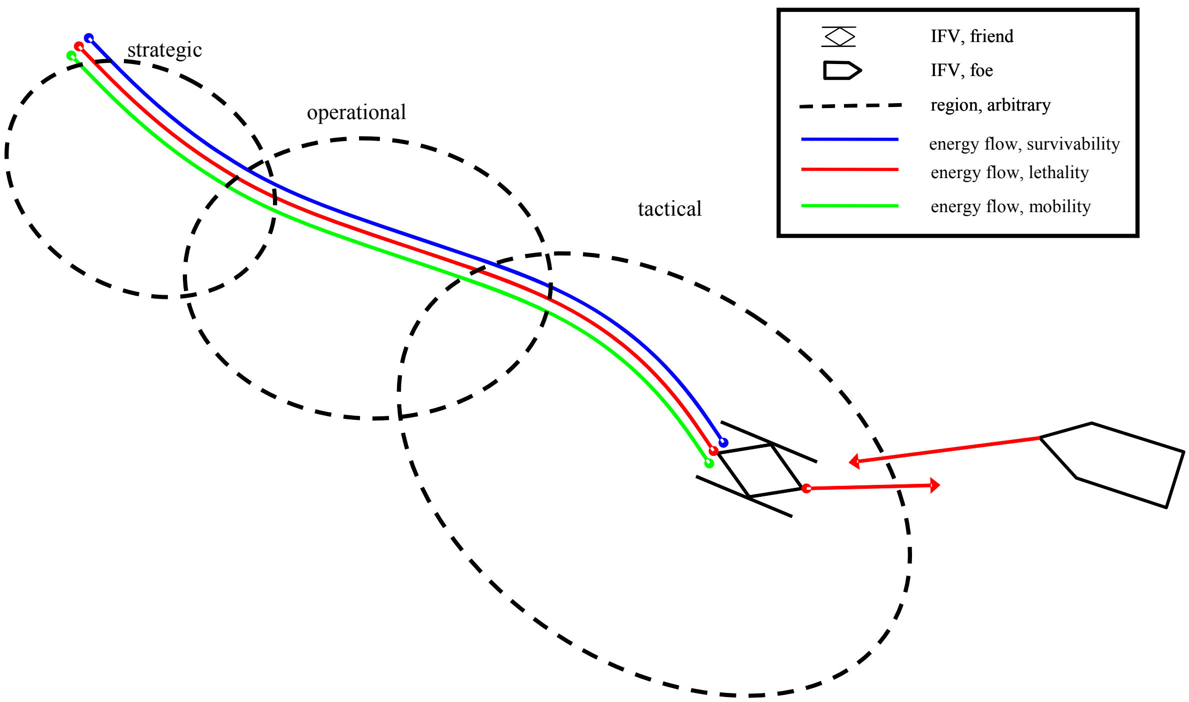


Figure 20: Notional IFV scenario with three levels of overlapping arbitrary regions and energy flows for survivability, lethality, and mobility (not to scale). This figure is intended to illustrate how after a platform is transported across regions of responsibility for each level of war, sustainment of combat power with regard to each attribute occurs along notional conduits of energy.

2.4.1.1 Mass

Mass at the tactical level is required to both defend against and to employ a range of munitions crossing the control surface. These include small-caliber bullets as slight as

100 g, large cannon projectiles weighing 5 kg, and even IED threats with yields greater than 100 kg. If survivability is compromised, then the system has been catastrophically insulted and a new system must be deployed through the control regions at the strategic and operational levels. The scaling of mass for tactical mobility includes low and high ranges for a fighting vehicle curb weight. The range for fighting vehicle mass extends from 5,000 kg upward to 40,000 kg. At both the operational and strategic level, the range of mass related to survivability matches that associated with mobility. Survivability, being integral to the platform, demands that these two levels transport this mass intertheater (strategic) and intratheater (operational). A nonsurvivable platform will require replacement of the same order of mass. The catastrophic destruction of a friendly vehicle is, by definition, a repair done via replacement. Lethality and mobility mass ranges are also similar at the operational and strategic levels. The lower limit represents the replenishment of ammunition and fuel stores onboard. For an IFV, this can amount to 1000 kg of ordnance and 500 kg of fuel, respectively. The upper limit represents the mass associated with platform emplacement into and through the theater. Table 13 has the ranges of mass for the principal attributes at the three levels of war. This information is also depicted in Figure 21 using the same convention to delineate the attributes at the levels of war presented in Table 13.

Table 13: Mass Scaling for Survivability, Lethality, and Mobility at the Three Levels of War

Attribute ▶ **Level of War ▼**	**Survivability**	**Lethality**	**Mobility**
Tactical	100 g — 100 kg (bullet — shell)	100 g — 100 kg (bullet — shell)	5,000 kg — 40,000 kg (small — large vehicle)
Operational	5,000 kg — 40,000 kg (small — large vehicle)	1000 kg — 40,000 kg (magazine — vehicle)	500 kg — 40,000 kg (fuel cell — vehicle)
Strategic	5,000 kg — 40,000 kg (small — large vehicle)	1000 kg — 40,000 kg (magazine — vehicle)	500 kg — 40,000 kg (fuel cell — vehicle)

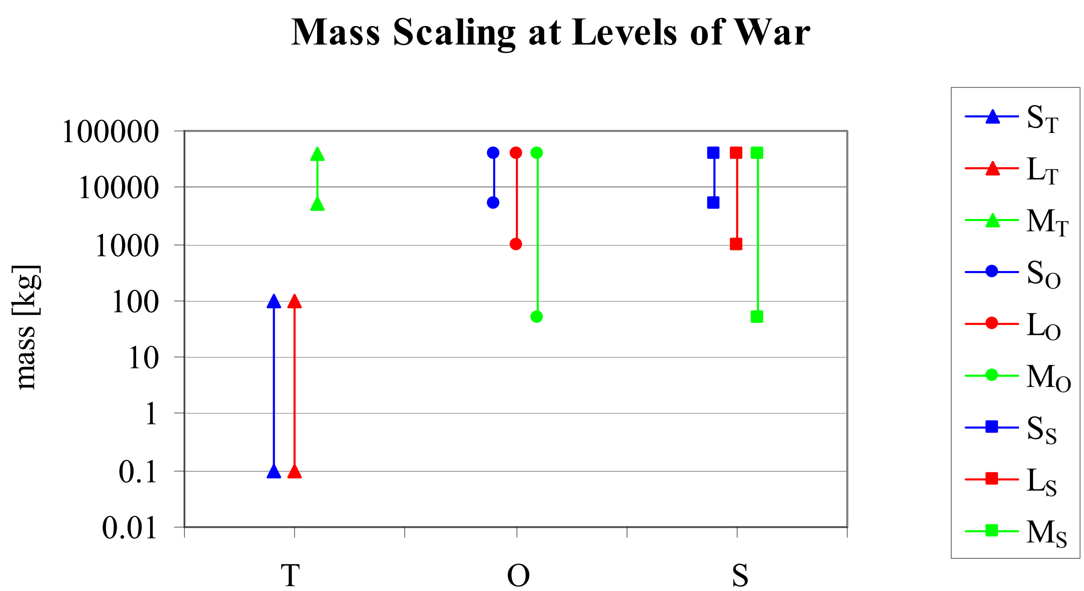


Figure 21: Mass scaling for survivability, lethality, and mobility at the three levels of war. Blue denotes survivability, red denotes lethality, and green denotes mobility. Triangles are for the tactical level, circles are for the operational level, and squares are for the strategic level.

2.4.1.2 Length and Time

The length and time scaling for survivability at the tactical level of war represent the spatial and temporal ranges associated with defending against threat munitions. In other words, the minimum and maximum armor thickness one would expect to see on a fighting vehicle and the time inherent in retarding an incident threat. For survivability considerations, this only considers vulnerability and notably neglects the hypothetical opportunities that could afford the victim the ability to avoid insult, e.g., early warning, visual detection of imminent threat, etc. Likewise, the length and time scaling for lethality are the range of distances across which the ground combat vehicles engage. Finally, the length and time scales under the mobility heading cover the shortest dash to a three-day, relatively long-range mission. The length and time ranges for the operational and strategic levels are all the same across the three principal attributes. These ranges are approximates for how fast and far these levels typically operate globally.

Table 14: Length Scaling for Survivability, Lethality, and Mobility at the Three Levels of War

Attribute ▶ **Level of War ▼**	**Survivability**	**Lethality**	**Mobility**
Tactical	10 mm — 1000 mm (thin — thick armor)	10 m — 5 km (short — long engagement)	100 m — 100 km (dash — excursion)
Operational	100 km — 1000 km (ranges of operation)	100 km — 1000 km (ranges of operation)	100 km — 1000 km (ranges of operation)
Strategic	1000 km — 10,000 km (ranges of operation)	1000 km — 10,000 km (ranges of operation)	1000 km — 10,000 km (ranges of operation)

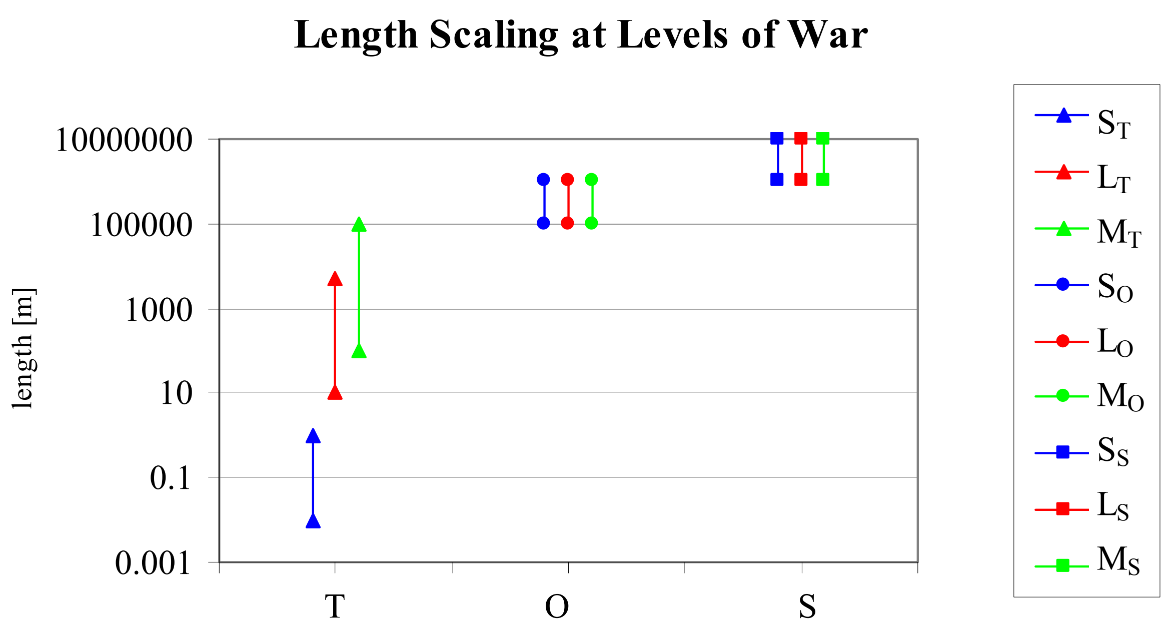


Figure 22: Length scaling for survivability, lethality, and mobility at the three levels of war. Blue denotes survivability, red denotes lethality, and green denotes mobility. Triangles are for the tactical level, circles are for the operational level, and squares are for the strategic level.

Table 15: Time Scaling for Survivability, Lethality, and Mobility at the Three Levels of War

Attribute ▶ Level of War ▼	Survivability	Lethality	Mobility
Tactical	1 ms — 1 s (impact event range)	10 ms — 10 s (launch event range)	10 s — 3 days (dash — excursion)
Operational	3 days — 10 days (response time range)	3 days — 10 days (response time range)	3 days — 10 days (response time range)
Strategic	10 days — 1 year (response time range)	10 days — 1 year (response time range)	10 days — 1 year (response time range)

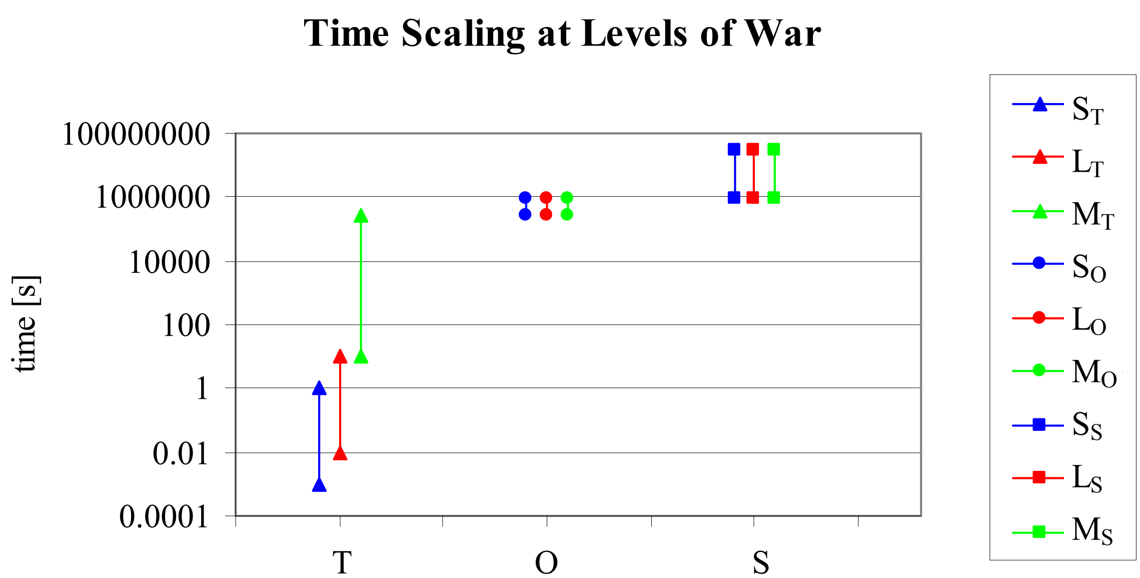


Figure 23: Time scaling for survivability, lethality, and mobility at the three levels of war. Blue denotes survivability, red denotes lethality, and green denotes mobility. Triangles are for the tactical level, circles are for the operational level, and squares are for the strategic level.

The brief scaling analysis demonstrates that, for an individual IFV depicted in a notional scenario (Figure 20), the tactical level experiences the greatest variations in mass, length, and time scales. By inspection, the operational and strategic length scales are fairly stable, but the tactical level operates over a length encompassing a brief dash all the way to a long distance expedition. If the entire conduit from strategic through operational to tactical level is considered a whip, then the end—the tactical level—experiences the greatest fluctuations. Additionally, each level experiences a unique range of mass, length, and time scales with respect to other levels. What this shows is that the tactical level requires large inherent robustness to operate across a wider range of mass, length, and time scales. Finally, a system optimized for the operational or strategic level may place constraints that limit the functional capacity and performance capabilities at the tactical level.

Another observation from this scaling analysis was the huge penalty in mass associated with inadequate survivability. At each level, the upper and lower ranges of mass, length, and time are with consideration for failure to accomplish a mission. The minimum mass associated with a failed kinetic engagement might be a demand for more resupply of ammunition through the control regions. Alternatively, an unsuccessful movement could require extra fuel to support an alternate route. Thus, the minimum cost for failure with respect to survivability is at best extended engagements and combat vehicle overhaul. But, at the other extreme, the maximum cost for failure with respect to survivability lies the potential for total vehicle replacement and, more tragically, the complete loss of crew. In other words, the strategic and operational level always pay a hefty price to emplace a platform and its crew. Any benefit of reducing net survivability, e.g., to achieve strategic or operational mobility, can be quickly offset if that platform and crew are damaged—or worse—lost to enemy fire.

2.4.2 Exercise II: Fielded Combat System Performance Specification Analysis

A generally accepted truism about combat vehicles is that superior protection and firepower normally come at the expense of transportability or the metrics associated with good operational and strategic mobility. The massive armor and heavy weapons associated with the apex predators of the battlefield come at the expense of high gross vehicle weights, which are not conducive with easy movement inter and intratheater. The purpose of Exercise II was to further explore the merits of this truism by looking at existing combat vehicles while employing the levels of war construct for the principal attributes. A set of currently fielded combat platforms, ranked by relative performance within the survivability, lethality, and mobility construct, elicited affinities between the principal attributes at the three levels of war. A matrix was populated with fielded candidate combat vehicle specifications representing two tanks, two IFVs, two tracked APCs and two wheeled APCs (Table 16). Principal attribute rankings at the tactical level were a function of two metrics selected for their universal merit. At the operational and strategic level, the principal attribute rankings were assumed to be a function of one metric consistent with the mass, length, and time scaling analysis done in a previous section. Table 16 contains the specification data for the eight fielded vehicles: M1A1 tank (U.S.), T-72 tank (Russian), M2A2 tracked IFV (U.S.), BMP-3 tracked IFV (Russian), M113 tracked APC (U.S.), YW531 tracked APC (Chinese), Stryker wheeled APC (U.S.), and the WZ551 wheeled APC (Chinese).[115] Appendix 2 contains reference drawings and countries of origin for each vehicle used in this exercise.

[115] Foss, Christopher F. *Jane's Armor and Artillery, 2006-2007*. Virginia: Cambridge University Press, 2006.

Table 16: Specification Data for the Fielded Combat Vehicle Set[116]

metric [unit] Attribute$_{level}$	**BMP-3 tracked IFV Russian**	**M1A1 tracked tank U.S.**	**M113 tracked APC U.S.**	**M2A2 tracked IFV U.S.**	**Stryker wheeled IFV U.S.**	**T-72 tracked tank U.S.**	**WZ551 wheeled IFV U.S.**	**YW531 tracked APC U.S.**
mass [kg] S_T	18,700	54,545	11,253	22,940	15,240	44,500	15,300	12,600
RHA_{eq} [mm] S_T	30	600	20	50	30	300	10	10
caliber [mm] L_T	100	120	12.7	25	12.7	125	25	12.7
CAL [#] L_T	6,540	12,440	2,000	3,100	500	2,345	1,400	1,120
v_{max} [km/hr] M_T	70	72.42	60.7	66	100	80	85	65
P/w [hp/tonne] M_T	27	27	19	21	20	19	17	25
armor ρ'' [kg/m^2] S_O	1140	2890	1250	1360	840	2700	920	1220
ammo ρ [#/m^3] L_O	127	181	83	51	10	30	30	36
η_{fuel} [km/l] M_O	1.20	0.26	1.33	0.73	2.03	0.48	2.00	1.11
vehicle ρ [kg/m^3] S_S	362	793	466	378	306	569	329	408
r_{ammo} [mm/m] L_S	50	53	10	44	7	7	5	10
$mass^{-1}$ [1/kg]$\times 10^{-5}$ M_S	5.35	1.83	8.89	4.36	6.57	2.25	6.54	7.94
length [m]	7.14	7.92	4.86	6.55	6.95	6.95	6.65	5.48
width [m]	3.15	3.65	2.69	3.61	2.74	4.75	2.8	2.98
height [m]	2.3	2.38	1.85	2.57	2.62	2.37	2.5	1.89
range [km]	600	498	480	483	500	480	600	500
fuel [l]	500	1907	360	662	246	1000	300	450
volume [m^3]	52	69	24	61	50	78	47	31

[116] Christopher Foss, *Jane's Armor and Artillery, 2006-2007*. Virginia: Cambridge University Press, 2006. All dimensional values (length, width, and height) are reported as they are listed in Jane's. All derived values have been rounded appropriately.

A few notes about the specification data are necessary before proceeding further. First, due to the sensitive nature (from a security perspective) of survivability metrics, the values for RHA_{eq} are provided as good estimates. Second, the combat ammunition load value is a composite number for the various weapons onboard. For example, the M1A1 Abrams tank carries no less than three sizes and several types of ammunition: 120 mm main gun , 0.50 caliber heavy machine gun, and 7.62 mm coaxially mounted machine gun. Third, the armor areal density value was found in a similar process for equating composite armor to RHA_{eq}.

To a first approximation, each metric was associated with a principal attribute and level of war. For example, the capital letter beneath the units denotes the principal attribute, and the subscript capital letter indicates the level of war. For example S_T is a metric contributing to survivability at the tactical level.

Mathematical representations for operational and strategic metrics are provided as Equation 3–Equation 7. Equation 8 demonstrates how the presented area scales with vehicle mass, if the overall shape is assumed to be a rectangular prism with a 2:1 aspect ratio for vehicle length to width.

$$\rho_{\mathrm{vehicle}} = \frac{m_{\mathrm{vehicle}}}{V_{\mathrm{vehicle}}} \qquad \text{Equation 3}$$

$$\rho_{\mathrm{ammo}} = \frac{CAL}{V_{\mathrm{vehicle}}} \qquad \text{Equation 4}$$

$$\rho''_{\mathrm{armor}} = \frac{m_{\mathrm{vehicle}}}{A_{\mathrm{frontal}}} \qquad \text{Equation 5}$$

$$\eta_{\mathrm{fuel}} = \frac{range}{capacity} \qquad \text{Equation 6}$$

$$r_{\mathrm{armament}} = \frac{d_{\mathrm{bore}}}{h_{\mathrm{vehicle}}} \qquad \text{Equation 7}$$

$$A_{\text{presented}} = 10\left(\sqrt[3]{\frac{m_{\text{vehicle}}}{\frac{\rho_{\text{vehicle}}}{2}}}\right)^2 \qquad \text{Equation 8}$$

Using these preliminary metrics, the relative performance of the eight fielded vehicles based on the principal attributes of survivability, lethality, and mobility at the tactical, operational, and strategic levels of war were estimated as the average of their associated metrics. As a simple example, in the eight-vehicle set, if a candidate ranked second for RHA_{eq} and fourth for mass, then the average ranking for tactical survivability (a simple function of armor thickness and vehicle mass) would be (2+4)/2 = 3.

As a further explanation of how the calculations were conducted, the table below contains the basic algorithm followed to rank the candidate set. The tactical level attributes were functions of two metrics, while the operational and strategic attributes were functions of only one metric (Table 17).

Table 17: Vehicle Ranking Metric Formulas For Candidate *i*

Attribute $_{\text{Level}}$	**Function of**	**Units**	**Calculation of Rank_i**
S_T	RHA_{eq}, mass	kg, mm	$(\text{rank}(RHA_{eq,i}) + \text{rank}(\text{mass}_i)) / 2$
L_T	caliber, CAL	mm, #	$(\text{rank}(\text{caliber}_i) + \text{rank}(CAL_{,i})) / 2$
M_T	v_{max}, P/w	km/hr, hp/tonne	$(\text{rank}(v_{max\ i}) + \text{rank}(P/w_{,i})) / 2$
S_O	armor ρ''	kg/m^2	rank(armor ρ_i'')
L_O	ammo ρ	$\#/m^3$	rank (ammo ρ_i)
M_O	η_{fuel}	km/l	rank ($\eta_{fuel,i}$)
S_S	vehicle ρ	kg/m^3	rank (vehicle ρ_i)
L_S	r_{ammo}	mm/m	rank ($r_{ammo,i}$)
M_S	mass^{-1}	1/kg	rank (mass_i^{-1})

When the specification data was ranked by principal attribute at the three levels of war, interesting, but somewhat expected, outcomes were observed. The vehicles that scored best for strategic mobility (M_S)—platforms that are light, compact, and easily transportable by air—scored poorly for survivability and lethality at nearly all the other levels. Conversely, a vehicle that ranked high in tactical lethality and survivability (L_T and S_T) fared poorly in the mobility rankings at both the operational and strategic levels of war.

To exemplify this point in tabular form (Table 18), the best in class for each attribute (first and second place) are highlighted green and the worst in class (seventh and eighth place) are highlighted red. The M1 Abrams tank scored well in every area except operational and strategic mobility (M_O and M_S). However, the high performance of these battlefield apex predators comes at a steep price, namely extreme curb weight and a ravenous appetite for fuel. This penalized the ranking of the platform for operational and strategic mobility. Contrast the M1 Abrams platform with the Stryker APC, which was the top performer in operational and strategic mobility, but had a poor ranking in most of the other areas.

It should be noted that this simple exercise was not intended to directly compare main battle tanks to wheeled APCs, as this is a veritable "apples to oranges" comparison in the fighting vehicle domain. Clearly, the design objectives for a tank and an APC are entirely different; by design, they bring unique benefits, as well as performance inadequacies, in specific areas. Rather, the intention here was to explore and illustrate the conduciveness and exclusiveness of the principal attributes at the various levels of war, at which there is an inherent, qualifiable, if not quantifiable, competition.

Table 18: Principal Attribute Performance Rankings for the Combat Vehicle Set

	BMP-3 tracked IFV Russian	M1A1 tracked tank U.S.	M113 tracked APC U.S.	M2A2 tracked IFV U.S.	Stryker wheeled IFV U.S.	T-72 tracked tank Russian	WZ551 wheeled IFV Chinese	YW531 tracked APC Chinese
S_T	4	1	7	3	5	2	6	7
L_T	2	1	6	4	8	2	5	7
M_T	3	1	8	5	2	4	5	5
S_O	6	1	4	3	8	2	7	5
L_O	2	1	3	4	8	7	6	5
M_O	4	8	3	6	1	7	2	5
S_S	4	1	8	3	6	2	5	7
L_S	3	2	6	5	8	1	4	7
M_S	3	8	6	4	1	7	2	5

The rankings in this table were calculated using Equations 3–8 and the formulas described in Table 17.

These initial findings were further explored and visually depicted by comparing the absolute value of the difference for these best-in-class performers between the principal attributes at the levels of war. Platforms ranking in the top 2 or bottom 2 for an attribute at a specific level of war were analyzed by taking the absolute value of the principal attribute against each other recorded attribute. This data was then averaged and populated into the top portion of a quality function deployment (QFD) diagram, also known as the "roof" of a House of Quality (HOQ) in Figure 24.[117] For example, if a vehicle ranked first in tactical lethality and eighth in strategic mobility, then the intersection of those two terms (L_T and M_S) would be the absolute value of the difference $|1-8| = 7$.

[117] Kevin Otto and Kristin Wood, *Product Design: Techniques in Reverse Engineering and New Product Development* (New Jersey: Prentice Hall, 2001) 289-297.

A relatively low, average absolute value indicated a complementary relationship, while a high average absolute value pointed toward a negative correlation between the principal attribute at a particular level of war. The average range for absolute values was 6, and a scale employing four colors was used to help visually depict the relationships.[118] Strength of correlations was based on: 0–2, strong positive; 2–3, positive; 3–4, negative, and 4–7, strong negative. As mentioned earlier, these were plotted in Figure 24.

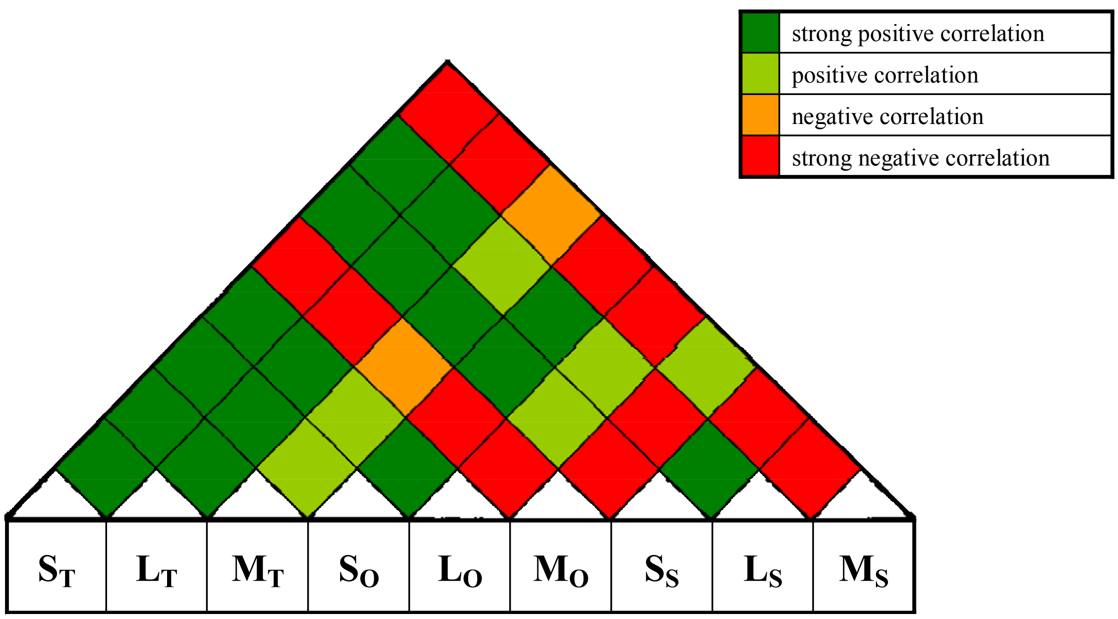


Figure 24: Correlation diagram for principal attributes at the three levels of war. This is essentially the roof of a house of quality (HOQ).

From the correlations depicted in Figure 24, it is clear that strategic and operational mobility (M_S and M_O) conflict with nearly every attribute at every level of war. This is not all surprising, since the metrics that contribute to a vehicle possessing good strategic and operational mobility, i.e., being light for ease of intertheater transport

[118] Two of the vehicles produced scores ranges from 1-8, while the other two presented ranges from 2-7, making an average range of 6 for the subjective delineations between strong positive, positive, negative, and strong negative correlations.

and having long operational range for ease of demand on fuel consumption, are achieved (with conventional technologies and materials) at the expense of physically constraining the design (combat vehicle) and reducing performance capabilities at the tactical level. Of the 8 correlations for strategic mobility, 6 were strong negatives and 1 was negative. Likewise, of the 8 correlations for operational mobility, 6 of the correlations were strong negatives and 1 was a negative. In other words, vehicles that ranked high for strategic and operational mobility ranked low for virtually all attributes at the levels of war, and vice versa. With respect to the tactical level, the attributes apparently correlated positively. There was a strong positive correlation between tactical survivability (S_T) and tactical lethality (L_T), meaning a vehicle that possessed good tactical survivability generally possessed good tactical lethality, and vice versa. A similar relationship was observed for tactical mobility (M_T), i.e., there was a strong positive correlation with both tactical survivability and tactical mobility. Combat vehicles designed to be the apex predators of the battlefield do so at the expense of operational and strategic mobility. Conversely, a vehicle design, constrained in mass and volume to achieve good operational and strategic mobility, appears intrinsically incongruent with the performance metrics contributing to tactical level attribute dominance.

2.5 Lessons Learned

- Just as trees need roots, a sound approach to developing a decision support framework directed upward (with branches) from the design or selection objective (trunk) should include a corresponding investigation downward to illuminate the guiding principles and underlying doctrinal basis for the pursuit (roots).
- The elements of combat power, the requirements for full spectrum operations, and a review of the principles of war, all strengthen the essentialness of advanced ground combat systems that provide soldiers with enhanced levels of protection, firepower, and mobility on future battlefields.
- A decision support framework built around the principal attributes of survivability, lethality, and mobility, provides a doctrinally sound and logical basis in which to organize and classify engineering metrics. The soundness is based on the direct linkages between those attributes and the U.S. Army doctrinal concepts, i.e., full spectrum operations, elements of combat power, principles of war, and the levels of war. The logicality is defended based on the use of the best practices and demonstrated methodologies in decision analysis, i.e., the prior use of the analytic hierarchy process (AHP) in military pursuits requiring the employment of a decision analysis method. However, as will be seen in Chapter 3, AHP is not without pitfalls, and the dangers associated with these shortcomings can potentially misguide a pursuit.
- A metric crosswalk qualitatively demonstrated the competing demands between principal attributes. Notably, the pursuit of higher survivability through conventional means suggested negative effects on platform lethality and mobility considerations.
- The tactical level of war experiences the greatest range in mass, length, and time scales for combat actions related to survivability, lethality, and mobility. The operational and strategic levels enjoy greater stability and narrower ranges of mass, length, and time for these dimensional scaling considerations.
- Parsing and discriminating the principal attributes at the three levels of war provided insight into the contrasting and complementary interests at each stratum. For a tactical asset like a ground combat vehicle, the concept of lethality and survivability at the operational and strategic levels of war remains elusive.
- Ranking of existing vehicle performance specifications demonstrated that strategic and operational mobility appear inherently incongruent with tactical survivability and lethality.

2.6 Conclusions

For over 100 years, fighting vehicles have played a critical role in the prosecution of ground warfare. As an integral component in the prosecution of full spectrum operations, and as a virtual generator/guardian of the elements of combat power, mobile and protected weapon systems are vital to the efficient and decisive execution of the U.S. Army's mission. At the level at which these platforms conduct operations, a combat platform's efficacy is a strong function of its core functional capabilities, i.e., its inherent survivability, lethality, and mobility.

Expanding this concept to the three levels of war enabled this role to be qualified at each stratum. With the principal attributes formally defined with respect to platform efficacy, these three attributes were parsed at the various strata of military operations. As previously stated, the tactical level is primarily focused on possessing the greatest combat power. The operational level is charged with initially emplacing and then sustaining that power throughout; as such, the main interest for this level is in those systems that can be moved easily at the military intratheater scale and supported efficiently and effectively over the course of sustained operations. The strategic level shares the tactical level's desire for the greatest capability, but balances those gains against the exchange of resources for that increased performance in order to accomplish a strategic mission. There are clear differences and intrinsic conflicts in the priorities and requirements at the microscale (tactical), mesoscale (operational) and macroscale (strategic) levels of war.

The analytic hierarchy process (AHP), a distinct method in decision analysis, allowed for the organization of the numerous combat vehicle metrics used to describe a fighting platform, into an easily collapsible form. This organization qualitatively illustrated the competing demands among the hierarchy via a virtual metric crosswalk. In this regard, survivability presented areas of confliction since at least seven metrics falling under this attribute were incongruent with other traits and principal attributes.

From an engineering perspective, the creation of the survivability–lethality–mobility framework itself may enable the designer to explore a larger region of design space. Instead of focusing on potentially insignificant specifications and design features, the abstraction of the problem into critical attributes (or sub-objectives) and corresponding traits could potentially aid in allowing singular efforts to observe the linkage in the design objective hierarchy. For the ground combat vehicle example, the classification of each metric beneath a principal attribute and secondary trait provides contextual understanding to the significance of the engineering effort within the global (system) pursuit of an advanced fighting vehicle.

Scaling of the dimensions of mass, length, and time with respect to the three principal attributes demonstrated that the tactical level of war encounters the greatest ranges with these parameters. It also showed that the mass penalty imposed on the operational and strategic levels is greatest for a failure to adequately protect a platform. For example, failure in mobility might incur supplemental fuel to accommodate movement on an alternate route, and failure in lethality might necessitate extra ammunition to destroy a threat, but failure in survivability means the vehicle was subject to insult that produced damage commensurate with incapacitation for the platform, crewmembers, or both.

The inherent competing demands with pursuing high survivability, along with high lethality and mobility, e.g., large mass and big size that work against transportability, hamper mobility, and consume weight and space from lethality systems, call for further innovation to break this conflict. For example, before composites were used, a machine design could rarely be both strong and lightweight. A similar innovation or series of breakthroughs is required to pursue higher levels of fighting vehicle protection in concert with the other tactical attributes contributing to battlefield maneuver. At the higher levels of war, it is again essential to break this conflict in order to achieve desirable operational and strategic objectives like inter and intratheater transportability that demand relatively small mass and volumes. Without trivializing the interconnectedness and challenges associated with pursuing greater lethality, and recognizing that greater weapon potency will surely incur a mass and volume penalty to the platform, it appears from the metric crosswalk exercise that most metrics associated with lethality can generally be pursued without significantly negatively affecting others.

When expanding this concept to the three levels of war, operational and strategic mobility are incongruent with nearly all other attributes at all levels of war. This matches historical combat vehicle performance in which an easily transportable platform was often not able to bring the protection and firepower commensurate with the demands of major combat operations. The Stryker vehicle fits this category; moreover, the required progression of armor upgrades is indicative of this initial survivability gap. Meanwhile, these upgrades significantly diminished the strategic mobility for which it was so rigidly initially designed. Survivability—the attribute that seems to incur the highest costs in scaling analysis, the greatest number of design conflicts in the metric crosswalk exercise, yet remains a high priority in the design and selection process—was the only attribute where the cost of failure can be terminal for both platform and crew. The high relative importance of survivability in contemporary efforts like the MRAP and GCV programs matches historical accounts of successful platforms, like the Abrams and Bradley.[119]

However, the pursuit of high survivability cannot be accomplished in isolation. The collective contributions of lethality and mobility surely contribute at some level to

[119] Richard Chait, John Lyons, and Duncan Long, *Critical Technology Events in the Development of the Abrams Tank: Project Hindsight Revisited* (Washington DC: National Defense University, 2005) 22-27.

the overall performance of a ground combat vehicle. In the next two chapters, commensurate levels of these attributes are explored, by popular vote, then by simulation. First, collective weightings of these attributes were solicited from mid-career U.S. Army officers to get a sense of their priorities and judgments. Then, the interactions and relative effects of the principal attributes of survivability, lethality, and mobility on simulated fighting vehicle performance in an arena representative of the contemporary operating environment were analyzed to assess which attributes matter most and to what degree synergisms and conflicts exist.

Chapter 3: Attribute Weighting and Candidate Vehicle Selection

> When those difficult cases occur, they are difficult, chiefly because while we have them under consideration, all the reasons pro and con are not present to the mind at the same time… I endeavor to estimate their respective weights… and thus proceeding I find at length where the balance lies.
>
> I have found great advantage from this kind of equation in what might be called moral or prudential algebra.
>
> —*Benjamin Franklin in a letter to the British scientist Joseph Priestly*, *1772* [120]

3.1 Introduction

In order to gain insight into the utility and functionality of a ground combat vehicle decision support framework built around the principal attributes of survivability, lethality, and mobility, an exercise typical of common practices used in a GCV selection process was conducted with a representative population of mid-career U.S. Army officers. This exercise included a solicitation to generate weighting values for the attributes representing critical functions for the vehicle design and selection, as well as an opportunity for respondents to overtly select a vehicle from a set of candidate designs. Several surprising results were observed: namely, the effect of information presentation methods on a decision maker's choice, as well as the potential dangers of presenting candidate data using directly additive weighting methods. For a complex system like a ground combat vehicle—one characterized by a high degree of interaction between the environment, user, threat, and proximal systems— directly additive weighting methods may be wholly unsuited as the fundamental premises do not fully consider these critical intricacies and dynamics. The general difficulty in validating the weighting values, as well as performance inextricably linked to such complex interactions, further questions the utility of such methods.

[120] This letter is often cited in decision analysis literature, especially those dealing with MADM.

3.2 Background

In the previous chapter, the generally accepted, functional requirements of a fighting vehicle were expressed via the principal attributes of survivability, lethality, and mobility. These attributes were subsequently broken down into associated secondary traits and contributory tertiary metrics. While this may be an acceptable framework to organize and compare raw data in an itemized fashion for engineering design purposes, it (as will be demonstrated) does not add much actionable information to a decision maker in the primitive form of a table or an attribute tree. Further synthesis of the information is required to refine it to an enriched, more immediately comprehensible, albeit potentially misleading, form. As Franklin pointed out in his letter to Priestly, appropriate weights must be incorporated into this "prudential algebra" to improve the decision making value of the information at hand, but the key question (as will be demonstrated) is *which* prudential algebra.

A common motivation shared by decision support tools is a concerted effort to supplement an apparent limited capacity of the human mind to manage information, what has often been described as the "magical number seven".[121] George Miller documented that the number of objects the average person can hold in working memory is 7 ± 2.[122] Today, this observation is commonly referred to as *Miller's Law*. In his influential paper, Miller offers three simple techniques to expand this capacity. He recommends that it is best to "(a) make relative rather than absolute judgments; (b) increase the number of dimensions along which the stimuli can differ; and (c) arrange the task in such a way that

[121] George A. Miller, *The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information*, (The Psychological Review, 1956, vol. 63) 81-97.
[122] Ibid.

we make a sequence of several absolute judgments in a row."[123] Miller's techniques reinforce the value of decision support tools that boost the limited working memory of the human mind by enhancing the quality of the information available at the time a decision is made. His recommendations for synthesizing data into relative comparisons (Figure 25) and to increase the number of dimensions for those relative (candidate) comparisons (Figure 26) were observed in the formation of the decision support tools developed in this chapter.

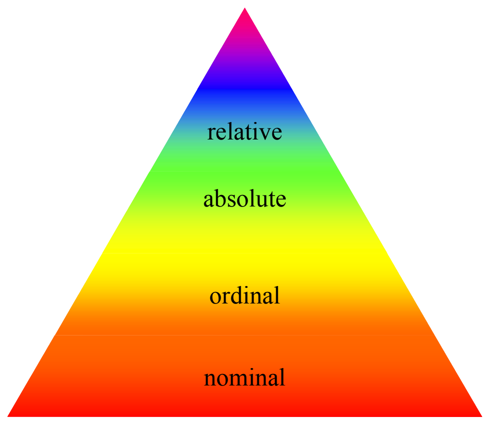


Figure 25: Types of data comparisons and the relative worth as a function of processing. Normalizing engineering metrics with respect to the best value among alternatives can form relative comparisons among the candidates.

Design and selection projects typically observe Miller's recommendations. Making relative comparisons among candidates, bifurcating program objectives into sub-criteria, i.e., increasing the number of dimensions that candidates can differ on, and explicitly stating go/no-go criteria, all aid the decision maker in the processing and utilization of information.

[123] George A. Miller, *The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information*, (The Psychological Review, 1956, vol. 63) 81-97.

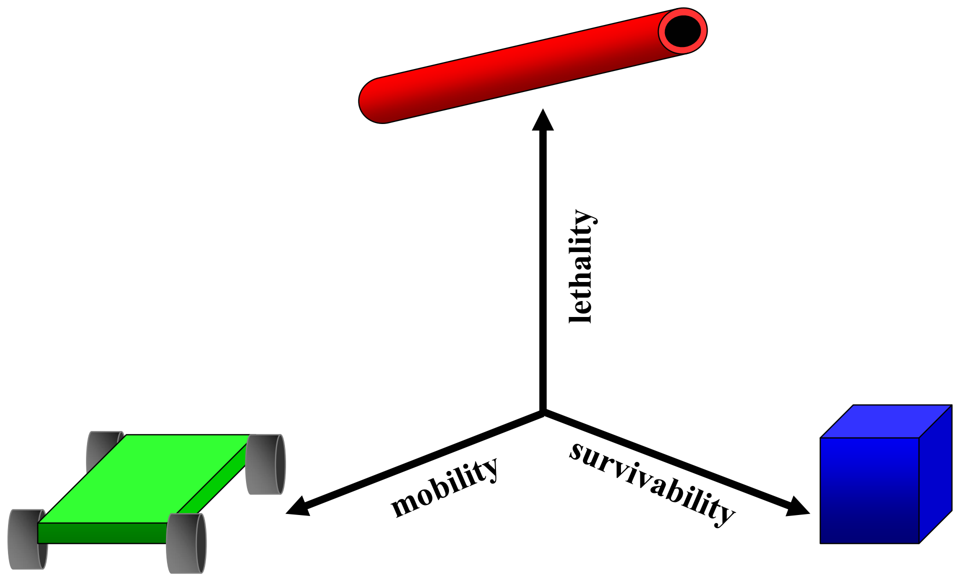


Figure 26: The dimensions used to evaluate candidate combat vehicles are considered as survivability, lethality, and mobility. At the extremes of each of these axes are a block of armor (blue), rolling chassis (green) and simple cannon (red).

When considering the additional dimensions or branches in a decision analysis framework, branches are typically weighted uniquely as not all attributes are deemed equally important. Decision makers can provide these weights either explicitly or implicitly through guidance. Given any individual's differing experiences, judgments, and wisdom, the weights assessed on attributes can vary (sometimes widely) among decision makers. To illustrate the sensitivity of decision maker derived weights, this chapter describes several exercises in which attribute weights related to fighting vehicle design and selection criteria were solicited from a representative population of U.S. Army officers. It was conjectured that the collective experiences of a group of combat-veteran leaders, all with varying levels of expertise and interest in combat vehicle design, would be a representative and perhaps meaningful source of shared insight concerning the generation of weights for the various criteria for future combat vehicle design and selection.

Having collected and processed the weighting data, the first research question was explored using the aforementioned survey populations. From the introduction (and restated here for clarity), this question was: **What effect does the use of decision support tools built around the principal attributes of survivability, lethality, and mobility, have on combat vehicle selection?** To answer this question, the respondents participated in a candidate vehicle selection exercise constructed about the principal attribute framework introduced in Chapter 2. Consistency tests were done to evaluate respondent selection when compared to weighting-derived selections. Analysis was performed in order to assess the value, if any, that the decision support tools lent to the respondents making their selections from a set of fighting vehicle candidate designs.

3.2.1 Methodology

Two groups of U.S. Army officers were surveyed in order to collect weighting data on the principal attributes, secondary traits, and tertiary metrics related to ground combat vehicle design considerations. Groups also subjectively rated their preference for four decision support tools, two of which were visual depictions of specification data synthesis. The other two support tools were standard, numeric matrices in varying display formats, i.e., raw data and normalized with respect to best criteria performer in the candidate vehicle set.

Subsequent to the portion of the survey dedicated to principal attribute, secondary trait, and tertiary metric weighting solicitation, the groups were asked to overtly rank 6 ground combat vehicles in order from most to least preferred. The specification data for these platforms was representative of 6 notional vehicles created for this comparative study. In this set of candidates, 3 vehicles were tracked and 3 were wheeled. Furthermore, in each subset of either wheeled or tracked vehicles, one was a well-armed (high lethality) candidate, one was a well-protected (high survivability) candidate, and one was a well-powered (high mobility) candidate. The archetypes within each set were designed to create competing demands among principal attributes as well as to compel the notional decision makers (respondents) to make trade-offs among candidate vehicle selection choices. Comparison tests were done to evaluate the consistency between vehicle ranking based on a given individual's weighting values and that same individual's overt selection.

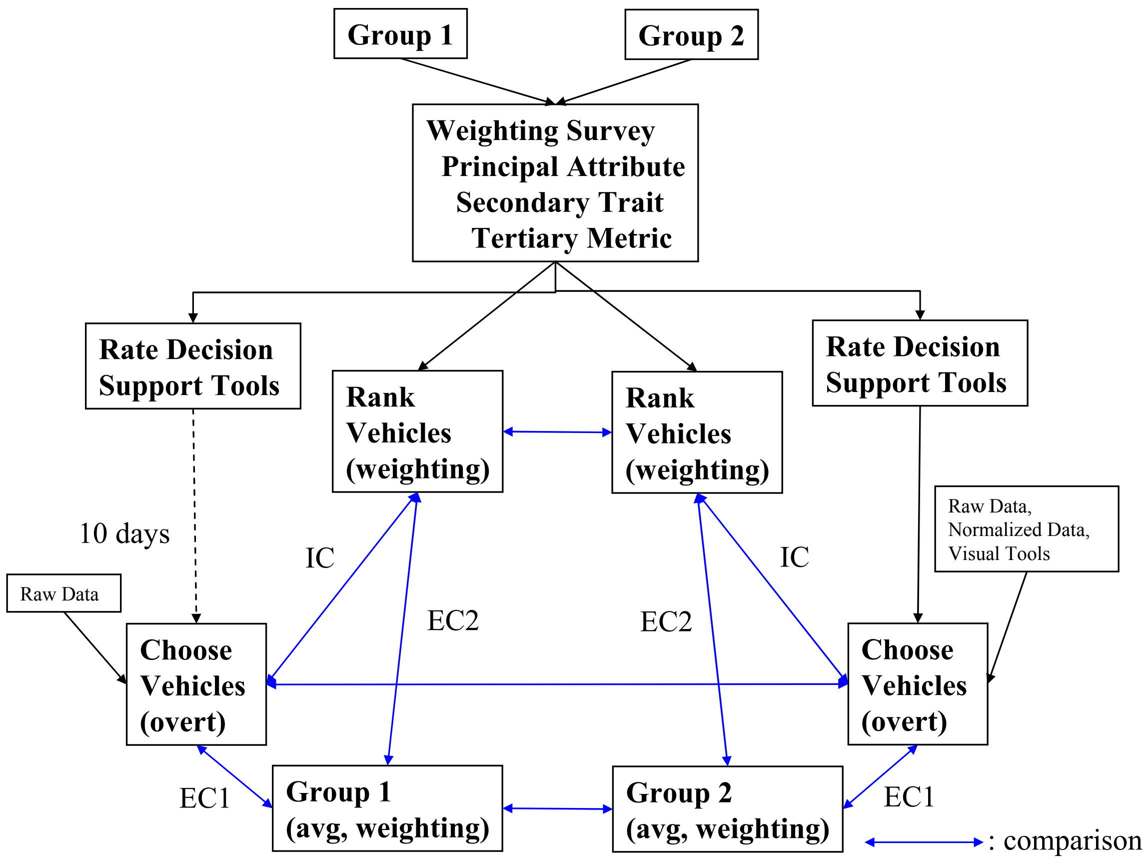


Figure 27: Flow chart for methodology designed to investigate the effect of decision support tools, built around the principal attributes of survivability, lethality, and mobility, on ground combat vehicle selection. Group 1 made overt choices using raw data only, while Group 2 had the same raw data, in addition to it normalized with respect to the top performer, and two graphical visualization tools. The terms *IC*, EC1, and EC2 are defined and discussed in § 3.6.3.

3.2.2 Weighting and Selection Survey

As presented previously, the effort described in Chapter 2 simply decomposed the relative merit of a combat vehicle into 3 principal attributes, 9 secondary traits, and approximately 70 tertiary metrics. Notably absent from that effort was a meaningful assignment of weighting values for these criteria; without these weights, a matrix of specifications describing a set of candidate combat platforms does not lend much value to a decision maker. In other words, the decision maker must manually interpret the data, cuing in on performance metrics of personal interest or value, and possibly missing the significance of an elusive design aspect.

To collect weighting data from the target U.S. Army officer population, a series of questionnaires were designed for a survey exercise. During a scheduled session, the proctor (author) issued these surveys for the purpose of gathering weighting data on the principal attributes, secondary traits, and tertiary metrics laid out in the previous chapter. A select set of soldiers serving in the U.S. Army's Acquisition Corps was identified as being reasonable candidates to both provide weighting data and make notional combat vehicle selection decisions.

For background, these officers were participating in a three-week functional area qualification course.[124] Attendees to this course are officers, serving at the rank of major, who had just begun bridging their tactical-level, warfighting career with the operational-level, materiel acquisition profession. The tactical-level experience was deemed helpful in providing insightful weights to the attributes, traits, and metrics that comprise the subjective significance of a combat vehicle. The operational-level experience was

[124] The U.S. Army Acquisition Corps is a specific functional area within the DoD. In the U.S. Army, this organization provides materiel development and life cycle management. Military positions in the U.S. Army Acquisition Corps include research and development, test and evaluation, program management, and contracting.

considered representative of the key decision making actions that a materiel developer may participate in during an activity focused on prioritizing the competing demands and complementary interests associated with an ambitious project, such as combat vehicle selection.

During the session, these heterogeneous groups of volunteer subjects were told that, given the theoretical requirement to design the next ground combat vehicle (GCV), they were being asked to provide input that could be used to generate the weighting values for the decision making process in the design and selection of the next generation fighting vehicle. It was made clear that this was a notional scenario and that the proctor (author) did not officially represent the U.S. Army GCV program. The weighting data solicited was with respect to the previously presented attributes, traits, and metrics used to describe a candidate combat vehicle. This was an individual survey, i.e., there was no collaboration among respondents. The proctor (author) addressed any points of clarification to the collective group during the survey administration.

Respondents were also asked to rank, in the order of importance, the collection of vehicle descriptors or engineering metrics, e.g., top speed, maximum engagement range, blast protection rating, etc. Additionally, these officers were asked to qualitatively assess their preference for some decision support tools under development. Finally, given a tactical scenario resembling the contemporary operating environment (COE) and a challenge to pick a future GCV platform from a set of candidates, the officers ranked a set of candidates from most to least preferred based on their combined judgment and use of a collection of standard decision support tools. Subjective preference for the decision support tools provided was also collected in order to rate the population preference for the developed aids.

Based on previous work with group decision making, as well as contemporary efforts focused on crowdsourcing, it was believed that the synthesized data from a group of interested and experienced respondents would be of higher value than that generated from a single decision maker.[125] The inclusion of a group of respondents, while complicating the conduct of the survey, may ensure that the weakness of a single decision maker's logic would not send the selection pursuit along a fruitless path.

3.2.3 Survey Process

Since collection of data from these officers is categorized by academia as human-subject research, a human-subject research proposal, including all required documentation, was submitted to the University of Texas at Austin's Institutional Review Board (IRB) in the Office of Research Support (ORS). "The IRB reviews human subject research projects according to 3 principles: first, minimize the risk to human subjects (beneficence); second, ensure all subjects consent and are fully informed about the research and any risks (autonomy); third, promote equity in human subjects research (justice)."[126] The review of this work was done through a six-step process (outlined in Table 19) based on submission and evaluation of the pertinent documentation listed in Table 20. Items 1, 2, 3, 8, and 9 from Table 20 were submitted to the IRB. The

[125] In William Easterly's 2006 book titled *The White Man's Burden: Why the West's Efforts to Aid the Rest Have Done So Much Ill and So Little Good*, (Penguin Press: New York), he uses the terms *planners* and *searchers* to describe the different approaches for gathering information. While a planner believes his knowledge and intuition provides him with the answer, a searcher "admits he doesn't know the answers in advance." Along this line of logic, given the complexity and uncertainty of assigning weighting values for the fighting vehicle attributes, a search method incorporating the weights of a group of respondents was preferred over a focus on a single decision maker. The concept of planner and searcher also corresponds to Treverton's framework for puzzles and mysteries.

[126] The University of Texas at Austin IRB instructional website, http://www.utexas.edu/research/rsc/humansubjects/.

questionnaire (item 2) was included in the survey (item 9). These documents are incorporated into this dissertation as Appendix 3–Appendix 6. [127]

Table 19: IRB Approval Process

Step 1	Submit title, type of review, and PI information.
Step 2	Submit researcher information and conflict of interest disclosure.
Step 3	Identify population of interest, outline consent methods, and state the location for which the research will be conducted.
Step 4	If applicable, list medical procedures and considerations for this study.
Step 5	List financial support and incentives for participation in this study.
Step 6	Provide additional documentation (Table 20).

Table 20: IRB Approval Documentation

1) Research Proposal	8) Consent Form
2) Questionnaire	9) Survey
3) Cover Letter	10) Recruitment Flyer
4) Email Recruitment Message	11) Telephone Script
5) Site Letter (if off campus)	12) HIPPA Form
6) Grant Proposal (DHHS)	13) Certificate of Consistency (DHHS)
7) Prior IRB Review Letter	14) Other Documentation

[127] The reference number for this study is: 2010090027. The IRB granted approval in September 2010 and was subsequently closed in April of 2011.

Using a pairwise rating form of solicitation, respondents were asked to rate the principal attributes (survivability, lethality, and mobility), secondary traits (related to survivability, lethality and mobility), and tertiary metrics (related to survivability, lethality, and mobility). The secondary traits associated with survivability included susceptibility, vulnerability, and repairability. For lethality, the secondary traits in the survey were acquisition, engagement, and target effects. For mobility, the secondary traits in the survey were cross country performance, roadworthiness, and robustness. Note that all attributes, traits, and metrics were organized alphabetically in the surveys so as to minimize any bias associated with the order of appearance. Table 21 lists the 30 tertiary metrics referred to in this survey exercise.[128] These were organized solely beneath the applicable principal attribute and not under a related trait.

[128] In order to make the survey more manageable, the original list of over 70 metrics was reduced to 30 (10 for each principal attribute).

Table 21: 30 Tertiary Metrics Used in the U.S. Army Officer Attribute Survey

Survivability		**Lethality**		**Mobility**	
Description	**Metric**	**Description**	**Metric**	**Description**	**Metric**
cross sectional area	A_{cross}	behind armor debris	BAD	center of gravity	cg
projected area, ground	$A_{footprint}$	combat ammunition load	CAL	vertical obstacle climbing height	h_{climb}
blast protection rating	BPR	force of recoil	F_{recoil}	power to weight ratio	P/w
combustible energy stored	$E_{combustible}$	kinetic energy	KE	range	range
mass efficiency of armor	e_m	cannon length	l_{cannon}	turning radius	r_{turn}
ground clearance	$h_{clearance}$	maximum effective range	MER	vehicle cone index	VCI_n
mass	mass	probability of kill	P_{kill}	maximum speed	v_{max}
modularity	modularity	time of flight	t_{flight}	horizontal gap width	w_{gap}
equivalent armor thickness in steel	RHA_{eq}	time to reload	t_{reload}	fuel efficiency	η_{fuel}
shape of belly, vee hull	vee hull	tuneability	tuneability	percent slope vehicle can climb	$\%_{slope}$

3.2.4 Pairwise Ratings

Pairwise ratings were used within the survey to solicit insight concerning the relative tradeoffs among the decision criteria used to evaluate candidate designs. The objective of this solicitation was to generate a priority or weighting vector which represented the apportioned affinity or preference for the criteria of interest. In addition to showing the relative value that a decision maker (or group of decision makers) places on each attribute, the weighting vector can be used in decision support tools to assist in conducting the "moral or prudential algebra" that Franklin described in his letter to Priestly. Developed by Saaty, this method asks respondents to rank the criteria in an ordinal fashion, then to express their affinity for a given criterion with respect to another using an arbitrary but predetermined scale.[129] As such, for n criteria it requires the respondents to provide $n(n-1)/2$ judgments or assessments. Given the increased number of relative judgments required, pairwise comparisons are not recommended when more than 7 criteria are being evaluated at the same level.[130] In addition to providing the investigator with greater insight on criteria affinity than that which is normally afforded by simply soliciting criteria rank or raw weighting values, the pairwise comparison method includes a means to check internal consistency in the assessment of rank and preference.

The group of pairwise comparisons comprising the decision maker's assessment on the criteria of interest comprise a square pairwise comparison matrix. Consider square matrix $\boldsymbol{A}$ where A_{ij} is the relative preference of criteria c_i with respect to c_j. The scale for preference, set by the investigator, should vary on some predetermined, graduated scale,

[129] Ching-Lai Hwang, Kwangsun Yoon, *Multiple Attribute Decision Making, Methods and Applications* (New York: Springer-Verlag, 1981) 41-53.

[130] T.L. Saaty, M.S. Ozdemir, *Why the Magic Number Seven Plus or Minus Two* (Mathematical and Computer Modelling, vol 38, 2003) 233–244.

e.g., 1–3 or 1–9, where a wider range provides finer resolution of the preference over the other, but at the added expense of increasing the deliberation of the respondent. A value of 1 indicates equal preference, while the high end of the scale, e.g., 9, indicates strong relative preference. In this study, a scale of 1–4 was used: 4 indicating "strongly favored", 3 signifying "favored", 2 meaning "slightly favored" and 1 meaning that the criteria were "equal" in preference to each other.[131]

$$A = \begin{bmatrix} \frac{c_i}{c_i} & \frac{c_i}{c_{i+1}} & \cdots & \frac{c_i}{c_n} \\ \frac{c_{i+1}}{c_i} & \frac{c_{i+1}}{c_{i+1}} & \cdots & \frac{c_{i+1}}{c_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{c_n}{c_i} & \frac{c_n}{c_{i+1}} & \cdots & \frac{c_n}{c_n} \end{bmatrix} = \begin{bmatrix} 1 & \frac{c_i}{c_{i+1}} & \cdots & \frac{c_i}{c_n} \\ \frac{c_{i+1}}{c_i} & 1 & \cdots & \frac{c_{i+1}}{c_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{c_n}{c_i} & \frac{c_n}{c_{i+1}} & \cdots & 1 \end{bmatrix}$$

As can be seen in ***A***, this matrix necessarily has diagonal values equal to 1. Moreover, the lower diagonal of the matrix is composed of reciprocal values from the upper diagonal according to $\boldsymbol{A}_{ji} = 1/\boldsymbol{A}_{ij}$. For example, $c_i/c_j = 1/(\ c_i/c_j)$. Once the matrix is populated, Morris showed that specific criteria weights can be found using the geometric mean of rows (Equation 9) for ***A***, while Saaty used an eigenvector method.[132] While both methods produce comparable results, it appears DECMAT uses the former geometric mean of rows, as calculations done to validate the method matched those produced by the software using Morris' described technique.

[131] This is also the scale used in the DECMAT software title.

[132] William T. Morris, *The Analysis of Management Decisions* (Illinois: Irwin, 1964).

$$x_i = \sqrt[n]{\sum_{j=1}^{n}\left(\frac{c_i}{c_j}\right)}, \text{ i = 1,n} \qquad \text{Equation 9}$$

While both methods are described for completeness, Saaty's method is described first. Saaty defines the n-dimensional weighting vector $\vec{w}_{max}$, such that it satisfies Equation 10 below, where λ_{max} is the maximum eigenvalue from the pairwise comparison matrix ***A.***

$$\begin{aligned} &[A - \lambda_{max} I]\,\vec{w}_{max} = 0 \\ &\lambda_{max} \equiv \max \lambda_i, \text{ i = 1,n} \end{aligned} \qquad \text{Equation 10}$$

Alternatively, Morris defines this n-dimensional weighting vector $\vec{w}_{max}$, according to Equation 11 and Equation 12. Due to the property of Equation 12, Equation 13 is necessarily true for the normalized weighting vector.

$$x_i = \sqrt[n]{\sum_{j=1}^{n}\left(\frac{c_i}{c_j}\right)}, \text{ i = 1,n} \qquad \text{Equation 11}$$

$$(\vec{w}_{max})_i = \frac{x_i}{\sum_{j=1}^{n} x_j} \qquad \text{Equation 12}$$

$$\sum_{i=1}^{n}(\vec{w}_{max})_i = 1 \qquad \text{Equation 13}$$

For those individuals who provide pairwise comparisons, Saaty also provides a way to check for the consistency of the weighting logic through a three-step process which lends itself to the calculation of a consistency index (*CI*) (Equation 15). For an n×n pairwise comparison matrix **A,** this index measures the difference between the maximum eigenvalue of **A** (λ_{max}) and the maximum eigenvalue of a theoretically, perfectly consistent matrix ($\lambda_{pc} = n$).[133] A perfectly consistent matrix is one in which the pairwise comparison values satisfy.

$$a_{ij} = \sum_{k=1}^{n} a_{ik} a_{kj} \qquad \text{Equation 14}$$

In Saaty's method for checking decision maker's logic, he subsequently defines the consistency ratio (*CR*) (Equation 16), which is the ratio of the consistency index and a random index (*RI*). The random index is the average *CI* that he obtained from 10,000 random pairwise comparison matrices.[134] As referenced in his 2008 paper, Xu argued that it *may* be an improper test for mistakes or instances of illogicalness with Saaty's baseline. In other words, "the consistency test should check for mistakes, rather than for non-randomness."[135] Given the community's acceptance of his method, as well as the widespread use in decision analysis software, Saaty's 30-year old pairwise comparison method was employed here with an appreciation for the ongoing efforts being done to possibly develop an improved technique.

In sequence, the check for consistency in Saaty's method of pairwise comparisons is as follows. Step one is to identify the largest eigenvalue in the n×n pairwise comparison matrix ***A***, followed by determining the value for λ_{pc}, which is assumed to be equal to *n* or the number of criteria. Step two is to calculate the consistency index *CI* using Equation 15, where *n* is the number of criteria. Step three is the final evaluation of the attribute weighting consistency ratio *CR*, calculated using Equation 16 with the

[133] Wei-Jun Xu, Yu-Cheng Dong, Wei-Lin Xiao, "Is It Reasonable for Saaty's Consistency Test in the Pairwise Comparison Method?" International Colloquium on Computing, Communication, Control, and Management, IEEE 2008, 284-298.
[134] Ibid., 296.
[135] Ibid., 284.

random index values *RI* from Table 22. According to Saaty, pairwise rankings having consistency ratios less than 0.1 are considered valid.[136]

$$CI = \frac{\lambda_{\text{max}} - \lambda_{\text{pc}}}{n-1} \qquad \text{Equation 15}$$

$$CR = \frac{CI}{RI} \le 0.1 \qquad \text{Equation 16}$$

Table 22: Random Index for Pairwise Comparison Matrices Including *n*-Criteria [137]

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

To illustrate application of this technique, a hypothetical military decision maker is asked to indicate preference between three major project considerations, namely cost, performance, and schedule, denoted C, P, and S respectively. Further, assume the decision maker ranks these criteria P, S, and C.

According to this ordering, performance has a higher priority than schedule, which has a higher priority than cost. Given 3 criteria, the number of inter-criteria observations required to populate ***A*** is $n(n\text{-}1)/2 = 3$. The first question involves assigning preference for P with respect to S which for the purposes of this illustration is to be "favored" or 3 on a scale of 1–4. Likewise, the preference for P with respect to C is assumed to also be "favored" with a numerical value of 3. Finally, the preference for S with respect to C is assumed to be "slightly favored" at a numerical value of 2. Hence, ***A*** is found to be:

[136] Wei-Jun Xu, Yu-Cheng Dong, Wei-Lin Xiao, "Is It Reasonable for Saaty's Consistency Test in the Pairwise Comparison Method?" International Colloquium on Computing, Communication, Control, and Management, IEEE 2008, 284-298.
[137] Adapted from Saaty, 1980.

$$A = \begin{bmatrix} \frac{c_1}{c_1} & \frac{c_1}{c_2} & \frac{c_1}{c_3} \\ \frac{c_2}{c_1} & \frac{c_2}{c_2} & \frac{c_2}{c_3} \\ \frac{c_3}{c_1} & \frac{c_3}{c_2} & \frac{c_3}{c_3} \end{bmatrix} = \begin{bmatrix} \frac{P}{P} & \frac{P}{S} & \frac{P}{C} \\ \frac{S}{P} & \frac{S}{S} & \frac{S}{C} \\ \frac{C}{P} & \frac{C}{S} & \frac{C}{C} \end{bmatrix} = \begin{bmatrix} 1 & 3 & 3 \\ 0.33 & 1 & 2 \\ 0.33 & 0.5 & 1 \end{bmatrix}$$

whose eigenvalues are 3.054 and -0.027 ± 0.404i, with 3.054 being the greatest.

Based on Morris' method, Equation 11 and Equation 12, the weighting vector corresponding to the criteria weights for P, C, and S is presented below. Note this weighting vector corresponds to the largest eigenvalue found from the pairwise comparison matrix. Morris foregoes the introduction of the largest eigenvalue in producing the weighting vector.

$$\vec{w} = \begin{bmatrix} 0.56 \\ 0.27 \\ 0.17 \end{bmatrix}$$

Alternatively, Saaty's eigenvector method produces a very similar weighting vector using Equation 10 and Equation 13. Again, this weighting vector corresponds to the largest eigenvalue found from the pairwise comparison matrix.

$$\vec{w} = \begin{bmatrix} 0.59 \\ 0.25 \\ 0.16 \end{bmatrix}$$

Finally, the consistency ratio (CR) can be found using Equation 15 and Equation 16. In this example, solving for *CR* is found to equal 0.05 which is less than 0.1 and demonstrates consistent logic in criteria rank and preference.[138]

As mentioned briefly, this weighting vector tells decision makers the relative importance of each criteria based on the preference values collected. In a decision matrix with normalized values for each criterion, the weighting values serve as the coefficients for each criteria value, with the sum of those products equaling the candidate score. In a decision matrix with criteria represented by non-normalized or dimensional values, the values from the priority matrix serve as the exponents in the product sequence of values for the criteria. A further demonstration of this latter calculation is provided in §3.6.1.

[138] DECMAT, a decision support software tool that will be introduced in §3.6.1 presents a consistency ratio as a percent. In the example provided, the consistency ratio would be reported as 95%, versus 0.05.

3.3 Attribute Weighting and Candidate Vehicle Selection Data

Two 75-minute survey sessions were scheduled with the Intermediate Qualification Course (IQC) coordinator. Officer groups attending the IQC at the IAT in September and November 2010 were surveyed in two separate exercises.[139] Both sessions were held on Friday afternoons and volunteer respondents were released from duty by the IQC coordinator before the survey, encouraging those disinterested with the survey content or topic material to refrain from participating. Notably, several did in fact depart.

3.3.1 Survey Group 1: September 2010

For Group 1, there were three objectives for the first survey exercise conducted in two phases separated by about 10 days. The first objective (Phase I) was to collect a catalog of weights derived from an experienced population of officer leaders regarding the 3 principal attributes, 9 traits, and 30 metrics comprising major components of a ground combat vehicle system.[140] The second objective (Phase I) was to obtain early feedback on several decision support tools intended to aid in visualizing candidate data. The third objective (Phase II) was to use this initial survey population as a control group, since their candidate vehicle selection process was done using only raw vehicle specification data.

Group 1 consisted of 24 U.S. Army officers (N = 24; 21 male, 3 female), and 14 and 10 hold degrees in the arts and sciences, respectively. In this group, 83% (20 of 24)

[139] Beginning in 2011, the Army moved the IQC course from the IAT in Austin, Texas to Redstone Arsenal in Huntsville, Alabama.
[140] In order to make the survey more manageable, the original list of over 70 metrics was reduced to 30 (10 for each principal attribute).

had graduate degrees. All respondents had combat experience, with 88% participating in more than one tour of duty in either OIF or OEF.

In Phase I, the individuals in Group 1 were asked to complete the attribute survey and to subjectively rate their preferential ranking of a group of decision support tool concepts. These are described further in Part VI of the survey in Appendix 6. This was an individual, non-collaborative exercise. Aside from the proctor (author) entertaining any general questions to the entire group, all respondents worked alone.

In Phase II, approximately 10 days after they completed the attribute survey and without being informed of the results, respondents in Group 1 were given a notional COE scenario to select a fighting vehicle for full spectrum operations and asked to rank order 6 candidate GCVs based on raw vehicle specification data presented alphabetically as candidate performance specifications (Table 23). The generation of the candidate vehicle data was done in a way to force tradeoffs and create intellectual angst for the decision makers since the candidate vehicle set was nondominated (see definition for nondominated on page 30). For example, the most survivable candidate was less capable with respect to its lethality and mobility. Even within a single attribute, there were tradeoffs. Considering survivability, the candidate vehicle with the thickest armor, candidate C, had the second best blast protection rating after behind candidate F. Table 23 was the only data format provided to Group 1 when they were asked to make their overt candidate vehicle selection. Again, this was an individual, non-collaborative exercise.

Table 23: Raw (Non-Normalized) Candidate Vehicle Specification Data

Metrics ► Candidates ▼	Chassis Wheeled or Tracked	a accel [m/s^2]	armor material	BPR blast rating [kg yield]	KE kinetic energy [kJ]	MER max eff range [m]	P/w power to weight [kW/ tonne]	RHA_{eq} armor thickness [mm]	v_{max} max speed [km/hr]
A	Track (steel)	3	Al	150	205	2200	11	54	64
B	Track (steel)	4	Ti	160	17	1800	12	18	71
C	Track (band)	3	DU	192	54	2500	14	250	60
D	Wheel (4x4)	6	Al	125	109	2100	24	39	73
E	Wheel (6x6)	10	Ti	70	16	1800	15	13	92
F	Wheel (6x6)	6	DU	195	12	1500	21	140	67

3.3.2 Survey Group 2: November 2010

For Group 2, there were two objectives for the second survey exercise conducted in a single phase. The first objective was again to collect a catalog of relative weights for the 3 principal attributes, 9 traits, and 30 metrics comprising major components of the GCV system. Based on the values derived from Group 1, ordinal rank was established for the principal attributes and secondary traits for Group 2's attribute survey. The second objective was to solicit candidate vehicles selection data using alternative candidate vehicle decision support tools—actually alternative methods to visualize/present the same data—but all built about the principal attributes of survivability, lethality and mobility.

Group 2 consisted of 21 U.S. Army officers (*N* = 21; 19 male, 2 female), and 13 and 8 hold degrees in the arts and sciences, respectively. In this group, 76% (16 of 21) had graduate degrees. All but two respondents (19 of 21) had combat experience in either OIF or OEF.

Given the same notional COE scenario to select a fighting vehicle for full spectrum operations, respondents in Group 2 were given the same candidate vehicle raw data as Group 1 plus three additional forms of decision support tool information.

One decision support tool was a normalized table of specification data with respect to top specification performance for each metric (Table 24). The next decision support tool was a bar chart depiction of normalized data organized beneath principal attributes with weighting values assigned and incorporated (Figure 28). Respondents were informed that a previous study had found survivability, lethality, and mobility to have weighting values of 0.45, 0.3, and 0.25, respectively, and that visual depictions of the data accounted for these weighting values. The final decision support tool was candidate comparisons of the principal attribute values from Figure 28 in two-dimensional form, i.e., survivability versus lethality, lethality versus mobility, and survivability versus mobility (Figure 29). In the same fashion as Group 1's survey exercise, respondents in Group 2 worked independently.

Equation 17 was used to calculate the lethality portion of the bar chart for candidate *i* (Figure 28). In this equation (as well as Equation 18 and Equation 19), 10 was a scaling factor used for aesthetic purposes, w_L is the weighting value assigned to lethality by Group 1 (0.3), n is the number of metrics associated with lethality (2) from Table 23, and $m_{L,j}$ are the metrics associated with lethality (kinetic energy and maximum effective range). Equation 18 was used to calculate the mobility portion of the bar chart for candidate *i*. In this equation, w_M is the weighting value assigned to mobility by Group 1 (0.25), n is the number of metrics associated with mobility (3) from Table 23, and $m_{M,j}$ are the metrics associated with mobility (acceleration, power-to-weight ration, and top speed). Equation 19 was used to calculate the survivability portion of the bar chart for candidate *i*. In this equation, w_S is the weighting value assigned to survivability by

Group 1 (0.5), n is the number of metrics associated with survivability (3) from Table 23, and $m_{S,j}$ are the metrics associated with survivability (armor material density, blast protection rating, and armor thickness). (It was later discovered that this bar chart visual decision support tool is similar to those based on a method frequented in the commercial software *Logical Decisions for Windows®.*[141])

$$L_i = 10 w_{\mathrm{L}} \sum_{j=1}^{n} \frac{1}{n} m_{L,\mathrm{j}} \qquad \text{Equation 17}$$

$$M_i = 10 w_{\mathrm{M}} \sum_{j=1}^{n} \frac{1}{n} m_{M,\mathrm{j}} \qquad \text{Equation 18}$$

$$S_i = 10 w_{\mathrm{S}} \sum_{j=1}^{n} \frac{1}{n} m_{S,\mathrm{j}} \qquad \text{Equation 19}$$

Unlike Group 1 that experienced a 10-day interval between their weighting and selection exercises, Group 2 conducted candidate vehicle selection immediately following the attribute survey exercise. Moreover, for Group 2 the three alternative decision support tools—normalized specification data, bar chart depiction of performance data, two-dimensional representations of candidate attributes—were included in the survey materials. As will be discussed later, the bar chart (Figure 28) was most preferred by Group 2, and the two-dimensional depictions (Figure 29) were least preferred.

[141] Screenshot examples of the described visualization methods can be viewed at www.logicaldecisions.com/prod01.htm.

Table 24: Normalized Candidate Vehicle Specification Data

Metrics ► **Candidates ▼**	**Chassis type** **Wheeled or Tracked**	**a** **accel**	**armor material density**	**BPR** **blast rating**	**KE** **kinetic energy**	**MER** **max eff range**	**P/w** **power to weight**	**RHA_{eq}** **armor thickness**	**v_{max}** **max speed**
A	Track (steel)	0.30	0.14	0.77	1.00	0.88	0.46	0.22	0.70
B	Track (steel)	0.40	0.24	0.82	0.08	0.72	0.50	0.07	0.77
C	Track (band)	0.30	1.00	0.98	0.26	1.00	0.57	1.00	0.65
D	Wheel (4x4)	0.60	0.14	0.64	0.53	0.84	1.00	0.16	0.79
E	Wheel (6x6)	1.00	0.24	0.36	0.08	0.72	0.63	0.05	1.00
F	Wheel (6x6)	0.60	1.00	1.00	0.06	0.60	0.86	0.56	0.73

One of three supplemental decision support tools provided to Group 2 (in addition to the raw data contained in Table 23) when they were asked to make their overt candidate selection.

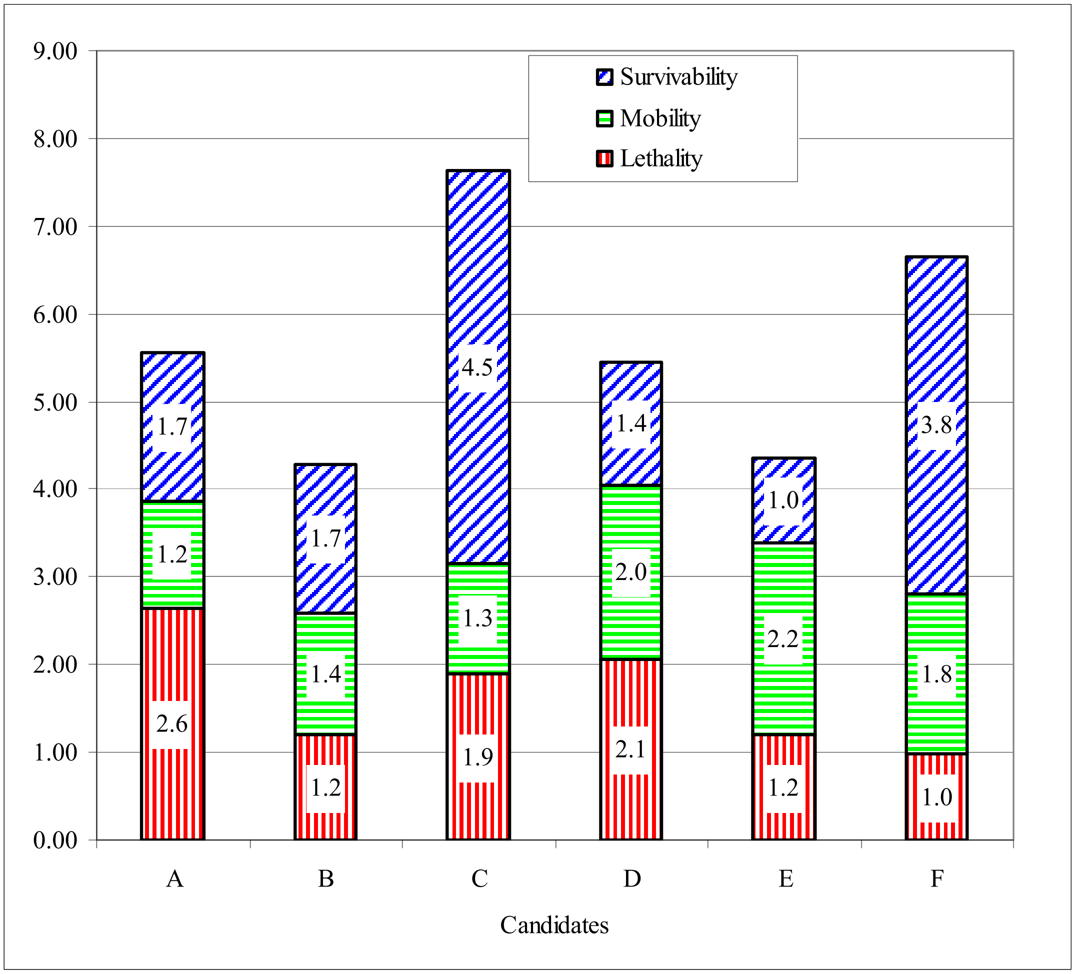


Figure 28: Bar chart depiction of relative survivability, lethality, and mobility for candidate vehicle set based on principal attribute weightings from Group 1 (survivability, 0.45; lethality, 0.29; and mobility, 0.26) and calculated using Equation 17–Equation 19. One of three supplemental decision support tools provided to Group 2 (in addition to the raw data contained in Table 23) when they were asked to make their overt candidate selection.

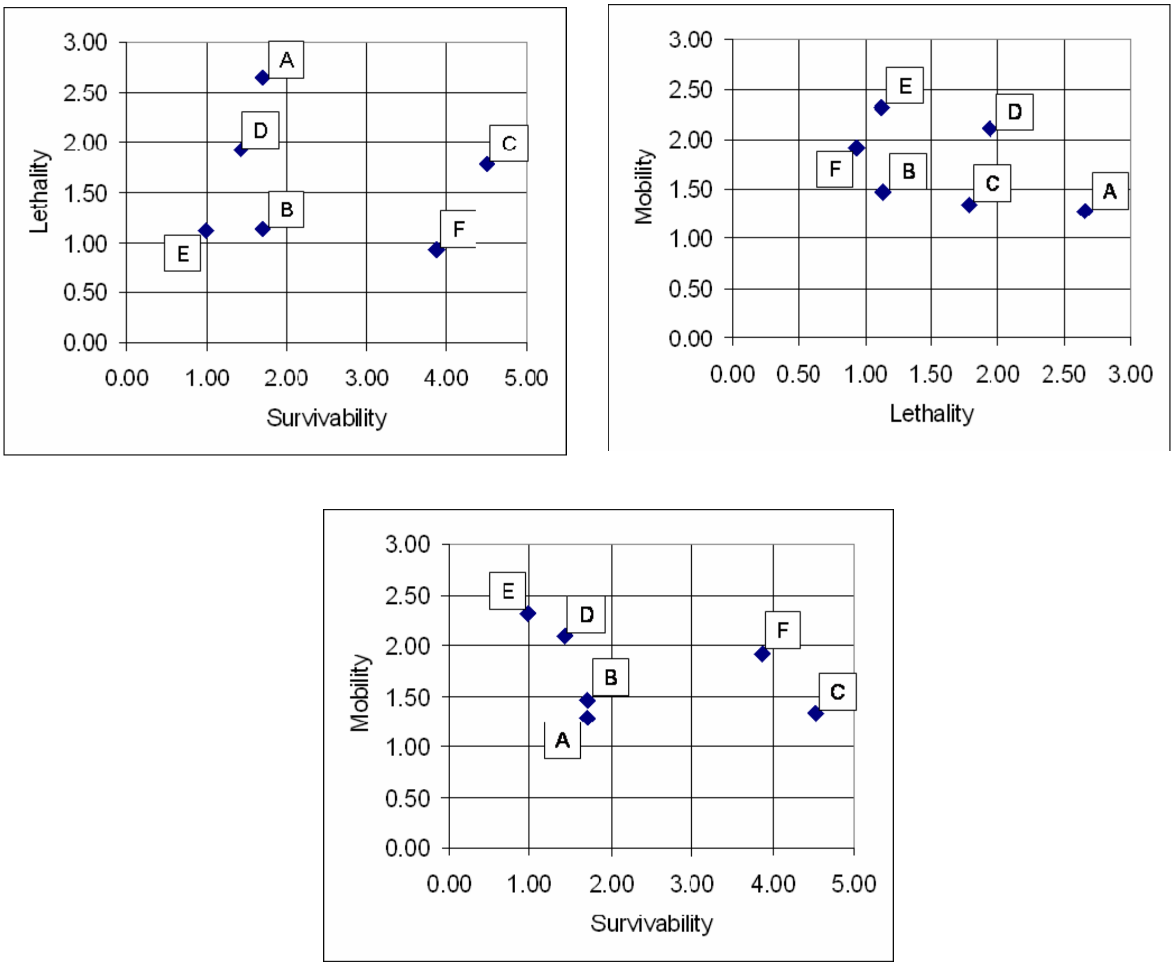


Figure 29: Two-dimensional depiction of relative survivability, lethality, and mobility for candidate vehicle set. The values for each candidate are taken from the bar chart values. For example, candidate A had a lethality value of 2.6, a mobility value of 1.2, and a survivability value of 1.7. The position of candidate A on each of the two-dimensional figures reflects these attribute scores. One of three supplemental decision support tools provided to Group 2 (in addition to the raw data contained in Table 23) when they were asked to make their overt candidate selection.

3.4 Attribute, Trait, and Metric Weighting Survey Values

Each group's individual ratings were entered into the DECMAT software in order to generate pairwise-derived weightings using Morris' geometric mean of rows method.[142] These weighting scores were then transformed to a weighted mean summing to 1. (For example, if the weightings of two notional attributes were calculated to be 1 and 3, then the weighted mean was found to be 1/(1+3) and 3/(1+3) or 0.25 and 0.75 respectively.) A summary of the average weights for each independent survey ($w_{\text{avg},1}$ and $w_{\text{avg},2}$), as well as a population-weighted average (w_{avg}) for the two surveys is provided in Table 25 (respondent raw data is tabulated in Appendix 7 and Appendix 8 for Group 1 and Group 2 respectively). The principal attribute weighting values collected from the 45 U.S. Army officers were fairly consistent with an average range of ±8% between the two groups. For the secondary traits, the average range was ±6% between the groups. In the tables provided, the colors correspond to the principal attribute (red for lethality, green for mobility, blue for survivability), and the highest weighted attribute and trait is in bold.

Table 26 contains the weighting values for the 30 tertiary metrics. These metrics were originally scored on an ordinal scale of 1–10 (most to least preferred), which was then inverted and transformed into weights summing to 1. The top three most highly valued metrics for each attribute are in bold in the tables, although it should be noted that many metrics received effectively the same weightings, making preferences between metrics virtually indistinguishable.

That said, these numbers can be interpreted as a representative set of relative value and numerical weights that a given group of military leaders assessed for the attributes, traits, and metrics for the selection of a ground combat vehicle. The collective combat experience of the group, as well as the variety of military functions performed by

[142] William T. Morris, *The Analysis of Management Decisions* (Illinois: Irwin, 1964).

these individuals, gives high subjective value but also perhaps lends robustness to the weights due to the different and unique perspectives each brought to the exercise (and likewise to the subsequent calculation of these weights).

Visual comparisons of weightings for principal attributes and secondary traits for each survey population are provided in Figure 30–Figure 33. Survivability was the highest weighted attribute, perhaps not unexpectedly given the propensity for damage done by IED attacks during the past decade in OIF and OEF. With respect to lethality, the respondents were mainly focused on the net effect on target, as seen by the high relative weighting of this lethality related trait. Surprisingly, respondents rated the ability to navigate cross country as the top mobility trait; inability to traverse cross country can make a combat vehicle highly predictable and susceptible to attack. The high weight assessed by the respondents on cross country movement reflects the survey participants recognition of the need for this capability in vehicle design. For survivability, the respondents weighted vulnerability as the most dominant trait for the attribute dealing with protection, again perhaps reflecting their past decade's experience in OIF and OEF.

The respondent values for the tertiary metrics were fairly evenly distributed among metrics. The average weighting value for the 30 metrics for both Group 1 and 2 was 0.10, with a standard deviation of 0.032 and 0.036 respectively. As such, the weighting values assigned to tertiary metrics were largely inconclusive. The small relative values of the standard deviation with respect to the average indicate that the respondents provided metric weighting values neutrally across metrics.

Table 25: Weighting Values for 3 Principal Attributes and 9 Secondary Traits[143]

Principal Attributes	Group 1 $w_{avg,1}$	Group 2 $w_{avg,1}$	Population Weighted Average w_{avg}
lethality	0.29	0.30	0.29
mobility	0.26	0.19	0.23
survivability	0.45	0.51	**0.48**
Lethality Traits			
acquire	0.25	0.20	0.23
engage	0.28	0.28	0.28
effects	0.47	0.52	**0.49**
Mobility Traits			
cross country	0.43	0.49	**0.46**
roadworthy	0.22	0.19	0.21
robust	0.35	0.32	0.34
Survivability Traits			
repairability	0.19	0.20	0.19
susceptibility	0.25	0.27	0.26
vulnerability	0.56	0.53	**0.54**

143 Bold items are the maximum values in the respective category (group of attributes or traits). The average value for both groups was found using a weighted average of the two groups of similar but distinct population sizes.

Table 26: Weighting Values for 30 Tertiary Metrics[144]

	Metric	Group 1 $w_{avg,1}$	Group 2 $w_{avg,1}$	Population Weighted Average w_{avg}
Lethality Metrics	BAD	0.06	0.04	0.05
	CAL	0.10	0.12	0.11
	F_{recoil}	0.05	0.06	0.06
	KE	0.09	0.11	0.10
	l_{cannon}	0.05	0.03	0.04
	MER	0.15	0.15	**0.15**
	P_{kill}	0.17	0.18	**0.18**
	t_{flight}	0.10	0.08	0.09
	t_{reload}	0.11	0.13	**0.12**
	tuneability	0.12	0.09	0.11
Mobility Metrics	**cg**	0.11	0.13	**0.12**
	h_{climb}	0.10	0.09	0.09
	P/w	0.09	0.12	0.10
	range	0.13	0.14	**0.14**
	r_{turn}	0.09	0.09	0.09
	VCI_n	0.10	0.07	0.09
	v_{max}	0.09	0.12	**0.11**
	w_{gap}	0.09	0.06	0.07
	η_{fuel}	0.09	0.10	0.09
	$\%_{slope}$	0.10	0.09	0.10
Survivability Metrics	A_{cross}	0.11	0.11	0.11
	A_{foot}	0.07	0.08	0.08
	BPR	0.18	0.16	**0.17**
	$E_{combustible}$	0.10	0.08	0.09
	e_m	0.09	0.08	0.09
	$h_{clearance}$	0.07	0.07	0.07
	mass	0.09	0.08	0.08
	modularity	0.06	0.06	0.06
	RHA_{eq}	0.14	0.14	**0.14**
	vee hull	0.09	0.13	**0.11**

[144] Bold items are the top three values in the respective category of tertiary metrics. The average value for both groups was found using a weighted average of the two groups of similar but distinct population sizes.

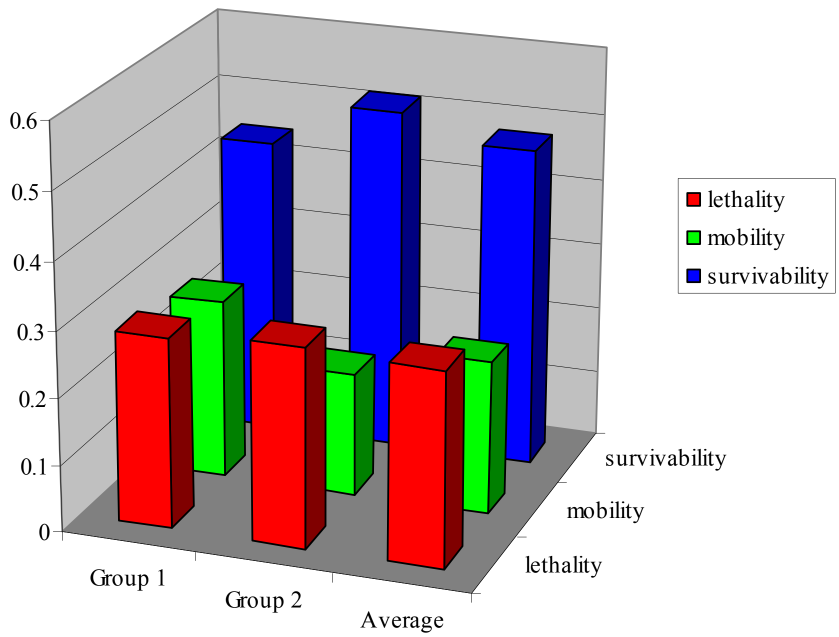


Figure 30: Attribute weighting values for lethality, mobility, and survivability for Groups 1 and 2. The average is the population-weighted average weighting values.

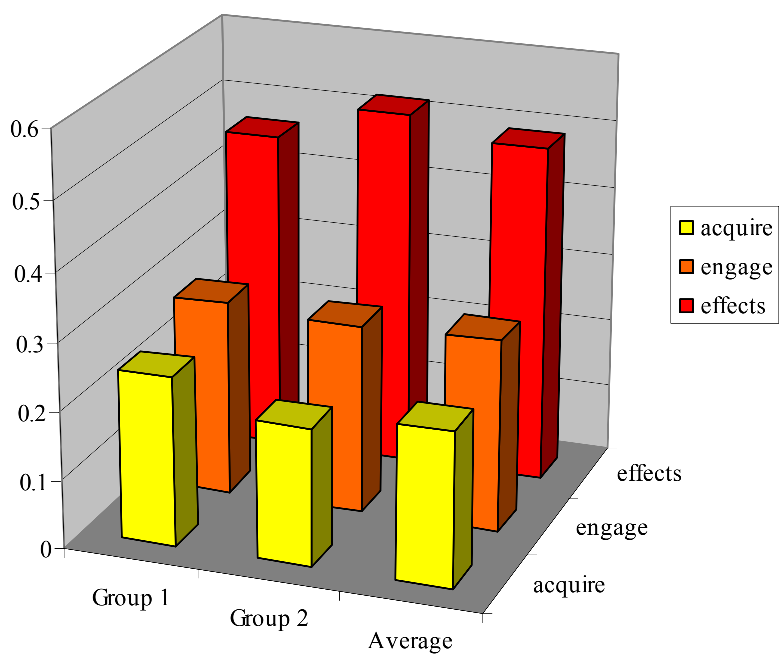


Figure 31: Lethality weighting values for target acquisition, engagement, and effects for Groups 1 and 2. The average is the population-weighted average weighting values.

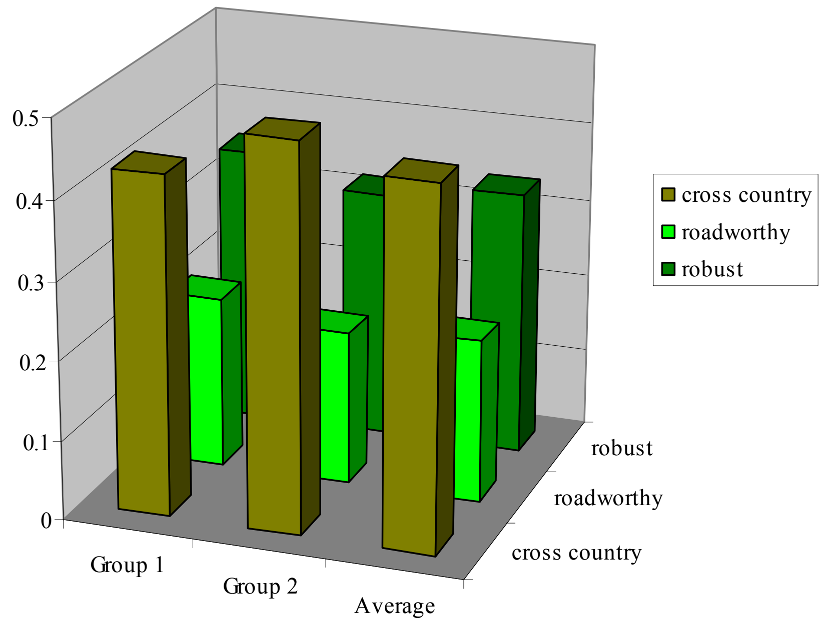


Figure 32: Mobility weighting values for cross country, roadworthiness, and robustness for Groups 1 and 2. The average is the population-weighted average weighting values.

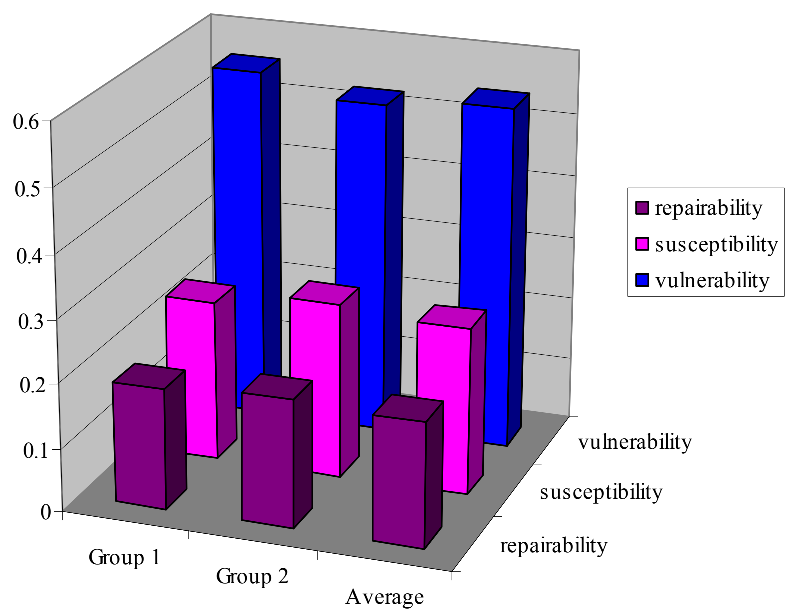


Figure 33: Survivability weighting values for repairability, susceptibility, and vulnerability for Groups 1 and 2. The average is the population-weighted average weighting values.

3.5 Analysis of Weighting Values

The raw data collected from the Groups 1 and 2 (Appendix 7 and Appendix 8) and further refined into the individual and group collective averages presented in Figure 30-Figure 33, was analyzed to investigate the significance of the values. As previously presented, the population weighted average for the collective principal attribute weightings for the two groups for survivability, lethality, and mobility were 0.48, 0.29, and 0.23 respectively (Table 25). The resounding message from these surveys was that platform survivability was clearly more highly favored than either lethality or mobility, which were effectively equally favored. One may infer that combat veterans, having seen the aftermath of IED attacks and rocket propelled grenades (RPGs), know the importance of ensuring that crew members, who are exposed to an array of types of hostile fire, are protected from attack and remain invulnerable to insult.

As will be explained in the next chapter, heavy focus on the attribute of survivability to the exclusion of and/or without consideration for the impact on other attributes or on holistic vehicle performance, can produce an imbalanced platform that is actually less survivable on the battlefield. If the pursuit of survivability impedes mobility, then the platform can, in fact, be more susceptible to attack (larger target, restricted movement, slower rate of march, etc.). That said, the pursuit of greater survivability may be accomplished through alternative means not immediately obvious or conventionally considered when attempting to increase the protection, e.g., reducing footprint, increasing mobility, increasing stealthiness, etc.

3.5.1 Survivability

Focus on survivability was embraced decades ago during the conceptual creation of requirements for the Bradley IFV and Abrams tank. Historical accounts of the engineering efforts dealing with these fighting vehicles consistently refer to the criticality of vehicle survivability in the design, testing, and manufacture of these two platforms. The Abrams tank may have enjoyed a smoother process than the Bradley IFV, but the end state performance achieved for both vehicles was a well-protected and highly mobile source of firepower.

In similar fashion, the survey respondents prioritized survivability highest among the 3 principal attributes considered at this level of attribute hierarchy. However, the survivability shortcomings experienced by the respondents, which may have motivated such a strong response, may not have been due to intrinsic shortcomings in the survivability of the Abrams tank and Bradley IFV (a.k.a., legacy platforms) in combat operations conducted primarily in Iraq. While there have been combat losses associated with these two platforms (both from explosively formed penetrators (EFPs) and IEDs), most losses occurred on other types of platforms and transport vehicles. Both of these legacy platforms originated from a focused effort on achieving platform superiority in a peer-threat engagement. Products of an effort focused on achieving success in offensive and defensive operations, these legacy platforms demonstrated robustness and the ability to pivot from major combat operations into stability operations. Survivability metrics for both Abrams and Bradley were focused on conventional forms of protection like frontal armor and reduced silhouette. In reaction to the differences associated with fighting against an asymmetrical threat on a noncontiguous battlefield, both vehicles received armor upgrade packages to better protect the crews in the COE. For example, the tank urban survivability kit (TUSK) included such upgrades as a gun shield around the turrets and slat armor for the engine exhaust area.

In the COE, the majority of combat losses associated with enemy action on vehicles was initially on less protected platforms like HMMWVs, unmodified Strykers, and the array of transport vehicles not originally designed to protect crews against the insult vectors posed by threat operators in Iraq and Afghanistan. Likewise, while nearly every survey respondent was a combat veteran, the dominant priority in survivability's weighting could be interpreted as being more indicative of observed deficiencies in ill-conceived platforms that frequented operations in the early part of OIF and OEF and not specifically an indictment of legacy platforms. In recognition of this point, the respondent focus on survivability should be considered in the broad context of the large losses experienced in unprotected or poorly armored systems.

3.5.1.1 Vulnerability, Susceptibility, and Repairability

When analyzing the traits comprising survivability, well over half of the composite respondents' weighting was assigned to vulnerability (0.54), followed by susceptibility (0.26) and repairability (0.19). For review and completeness, this taxonomy established by Deitz et al., refers to a platform's ability to withstand insult (vulnerability), a platform's ability to avoid insult (susceptibility), and a platform's ability to recover from insult (repairability).

Notably, the respondents' weighting on vulnerability dominates the discussion on survivability. For example, the survivability shortcomings in fielded systems operating in Iraq and Afghanistan were addressed first via appliqué armor upgrades for existing platforms, and subsequently with the MRAP series of vehicles. As a result, these vehicles have impressive levels of (in)vulnerability; they are moderately armored in nearly every direction, possess thick, bullet resistant glass, have faceted bellies to reflect incident pressure, and ride high off the ground to improve their blast protection rating. But, and perhaps consequently, these vehicles are highly susceptible to attack. Retrofit designs like the MRAP present a large, distinct visual, acoustic, and pressure signatures, making them more susceptible and easy targets for IED and rocket propelled grenade (RPG) attacks. In other words, the pursuit of performance with respect to metrics comprising an (in)vulnerable platform can and do work counter to the trait of susceptibility.

In the survey, susceptibility received less than half the weighting of vulnerability (0.26 versus 0.54), although efforts to make the platform less susceptible work in a proactive fashion to avoid insult. This is in sharp contrast to reactively and passively dealing with a threat vector by reducing platform vulnerability. While being less vulnerable may be regarded as an "insurance policy" against the effects of threat insult, disregarding the benefits of being less susceptible to attack in the first place forsakes potential opportunities to pursue platforms having lower likelihoods of receiving an insult by reducing the enemy's ability to acquire and engage the platform. This low rating may suggest a lack of appreciation for this connection or opportunity.

Perhaps unsurprisingly, repairability scored less than 0.2—the lowest weighting of any of the 9 secondary traits surveyed. Respondents are apparently less concerned with regaining combat power after insult, but are more focused on adequately preventing (susceptibility) and absorbing or deflecting (vulnerability) an insult. This could be due to an implicit assumption of short engagements, or perhaps due to historically superior levels of lethality and firepower. In observation of MRAPs struck by IEDs, it could also be due to the fact that real-time to repair catastrophically or critically damaged platforms in theater is not feasible, and most vehicles are simply repaired by replacement.

3.5.1.2 Tertiary Metrics for Survivability

As mentioned previously in § 3.4, the data received for the weighting of metrics was generally inconclusive and may indicate the implausibility of asking such a heterogeneous group of mid-career U.S. Army officers to assess the relative importance of specific engineering design details. Furthermore, the "flatness" of the tertiary metric weightings may also reflect lack of knowledge with the engineering terms, uncertainty about, or disagreement as to their relative contribution to platform efficacy. At best, 3 of 10 metrics for each principal attribute were identified as being a consensus priority for the survey respondents.

With respect to survivability, the relative weight assigned to the top three metrics most likely reflect the persistent threat in the COE, i.e., the proclivity for attacks associated with IED strikes on vehicles: blast protection rating or BPR (0.17), equivalent thickness of rolled homogeneous armor or RHA_{eq} (0.14), and vee-shaped hull designed to reflect the incident pressure wave associated with the blast from an IED (0.11). These metrics are all related to the vehicle trait of (in)vulnerability. Metrics which contribute to a less susceptible platform accounted for less than 30% of the residual weighting of metrics for survivability. This supports the low collective regard for susceptibility at the secondary level.

For example, high achievement of the metrics of mass efficiency (e_m) cross sectional area (A_{cross}), and platform footprint (A_{foot}) all contribute to a less susceptible platform, but these metrics received an average weighting of 0.09. Again, this raises the question of the viability of interpreting tertiary metric data, since all metrics possessed nearly identical weights. It demonstrates that at this level of engineering fidelity, the broad interpretation of respondent data may be of little use, and may be time better spent conferring with experts in respective fields, e.g., armor, ballistics, etc. Being less susceptible is not as valued to the group of respondents as being less vulnerable, both from the average weighting for these secondary traits and from the weightings collected for tertiary metrics associated with these secondary traits.

3.5.2 Lethality

The remaining half of principal attribute weighting was nearly equally shared by lethality (0.29) and mobility (0.23). By all accounts, legacy platforms achieved dominating results against the peer threat systems that frequented engagements during the early parts of OIF. It is conceivable that as these tactical incidents fade from memory, the intrinsic value and associated weighting priority on lethality has faded as well. In that way, these legacy systems may be a victim of their own success. The achievement of lethal superiority on the battlefield is the result of decades of concerted effort in weapon system research and engineering. Notably, survey respondents who gave lethality a 0.29 weighting have typically only seen the overmatch of conventional systems engaging less potent threats. It is worth considering that without the means to deliver overwhelming firepower to a target, the role of a fighting vehicle in major combat operations is largely relegated to that of well-armored transport vehicle.

3.5.2.1 Target Effects, Engagement, and Acquisition

For a notional engagement, target effects deal with the culmination of the insult, from incident strike to rest. Target engagement refers to all action from commission of a lethal payload until imminent target strike. Target acquisition includes all proceedings leading up to the moment of what can be considered pulling the trigger. Target effects received a weight value of 0.49, with engagement and acquisition scoring 0.28 and 0.23 respectively. Similar to the pattern of ranking survivability's traits in a fashion favoring reverse sequential order (vulnerability higher than susceptibility), the survey respondents rated the end state of a lethal engagement and associated traits with the largest weighting.

This is a reasonable weighting, because generating a lethal design begins with consideration of the target; without adequate delivery of a lethal effect, the successful engagement and acquisition of a target are exercises in futility. That said, engagement and acquisition, can in their own respects, contribute to greater survivability. A threat system, once acquired, gives the friendly system's crew the opportunity to assess and potentially take evasive actions. Likewise, an engaged friendly threat system, even if its payload turns out to be of an inadequate scale or improper form, can occupy and prevent, at least temporarily, the threat system's ability to commit fires. Therefore, in the immediate context of lethality, the weightings appear to reflect a focus on design and commission of the potential payload commensurate with threat system incapacitation.

3.5.2.2 Tertiary Metrics for Lethality

The top three tertiary metrics for lethality were reserved for two of the three secondary traits. The probability of kill (P_{kill}), received a weighting of 0.18, nearly twice its fractional share in the ten metrics presented for lethality; it deals with the entire lethal event culminating in target effects. The metric maximum effective range (MER) is associated with target engagement since it deals largely with the external ballistic event; respondents gave it a weighting value of 0.15. Time to reload (t_{reload}), a metric also associated with engagement, received a weighting value of 0.12; during engagement, the ability to reengage a persistent threat or to fire at an additional target, is enabled by a small dwell time between initiating a loading action and commissioning the round.

3.5.3 Mobility

Mobility ranked last in principal attribute weighting at 0.23. Mobility and lethality—the analogs of the constituent elements of maneuver, firepower and movement—were assessed by the respondents to be nearly equal in importance. These assessments are consistent with the doctrinal definition of maneuver that values both equally as necessary elements in achieving performance overmatch against a foe. If maneuver is generated by both firepower and movement, then perhaps this weighting value appears appropriate in scale to lethality. Many vehicles operating in Iraq have operated in the relatively developed areas comprising the proximities and connecting routes of the forward operating bases. As such, contemporary mobility requirements deal mostly with roadworthiness. This is in sharp contrast to operations in Afghanistan where the extreme terrain limits all but the most capable vehicles from moving off established roads consisting of improved surfaces.

As an attribute, mobility is often thought of as the "bill payer" for the combat vehicle mass and volume dedicated to providing survivability and generating lethality. Unlike survivability and lethality, mobility advancements benefit from commercial pursuits in civilian industries, e.g., automotive engineering, agricultural engineering, etc. The respondents, having moved about on capable platforms meeting all the required roadworthy automotive demands in the COE, may have seen no need to weight this attribute higher.

3.5.3.1 Cross Country, Robustness, and Roadworthiness

The weighting values for mobility traits were a bit surprising. The ability to move cross country, i.e., the vehicle's capacity to move about on unimproved surfaces, was the top ranked trait with a weighting of 0.46. Robustness, i.e., the ability to navigate unforeseen or unusual obstacles like gaps and climbs, was ranked next highest with a weighting of 0.34. Roadworthiness ranked last was with a weighting value of 0.21. The latter was an interesting assessment since most excursions in Iraq deal with navigating improved surfaces conducive with high roadworthiness. However, being limited exclusively to roads makes a platform susceptible to attack, as the constraint to solely traverse established routes and improved surfaces increases the predictability of vehicular movement.

3.5.3.2 Tertiary Metrics for Mobility

The top three metrics identified for mobility were vehicle range (0.14), height of the center of gravity (0.12), and vehicle's maximum speed (0.11). The ability to conduct a long excursion, without refueling, was of slight preference to the other nine metrics. The center of gravity rating was most likely a reflection of the high rates of vehicle rollover experienced by the top-heavy MRAPs fielded in Iraq and Afghanistan. Achieving excellence in mobility benefits survivability (evasion during attack, unpredictable in movement). And as a shared partner with lethality in maneuver, the tertiary metrics related to the secondary traits of mobility can also contribute to lethality success as well.

3.5.4 Synthesis of Weighting Data

There was good agreement between the two survey groups for the weighting values at the first and second levels of the hierarchy. Survivability clearly ranked highest among respondents. Again, this is not surprising, given the heavy combat losses observed by the subjects in OIF and OEF as a result of IED attacks. Even in the absence of a defined peer threat, those surveyed still ranked lethality as a weighted priority, and the focus for this attribute was also echoed at the next level with high ranking for the trait related to generating effects on the target. Surprisingly, given the focus on urban operations, the population of officers questioned clearly saw cross country movement as a highly valued trait for mobility considerations.

Maneuver warfare experts approach an urban area with trepidation and typically classify it as highly constricted terrain. At a casual glance, it appears that a fight in an urban area provides the lowest requirements for mobility given that the surfaces are improved and the slope generally flat. Moreover, those that have fought in this environment often cite the propensity for canalization of equipment. The inherent spatial restrictions provide opportunities for the incorporation of obstacles that can demand bypassing movements and a requirement to sustain cross country movement. This also explains why robustness ranked close behind this trait.

At the tertiary level, no clear distinction between metrics arose. At best, the values enabled labeling of several metrics as slightly preferred. But the relatively small variation between the two groups and generally flat average levels indicated that the distinctions in weighting were greatest at the first and second levels of the hierarchy. Nonetheless, the first two are the most valued from a respondent input perspective, as objective and utility functions can be created to link small groups of tertiary metrics with the secondary traits. As the weighting survey moved down from principal to secondary to tertiary levels, the distinction in weighting data dropped as well. Even at the principal level, lack of insight or even an appreciation for the synergism and confliction between the attributes of survivability, lethality, and mobility, could produce weighting values not conducive with an appropriate vehicle selection. As generalists bringing a wealth of tactical experiences, operational management responsibilities, and educational backgrounds, the collective population of U.S. Army officers potentially provided robust weighting values for the principal attributes. Values could differ from, say, dedicated platform operators, vehicle design engineers, or tactical and operational commanders charged with directing combat power in the COE. In other words, the engineering value of weighting data, even at the secondary level, is best used to simply provide insight into user preferences and should not be interpreted as a direct quantitative measure of the relative merit of one trait or metric to another. Even to a practicing engineer, the assignment of a tertiary metric weighting would provide little or no guidance or information in the design endeavor of a combat vehicle without a prescriptive relationship as to how that metric contributed quantitatively or even qualitatively to vehicle efficacy.

Considering the survey population and their potential lack of appreciation for the complexity of a combat vehicle system operating in the dynamic environment of full spectrum operations, the attribute weighting survey exercises provided some general insight into how the principal attribute could potentially be incorporated into both conventional and envisioned decision support tools. The weighting values for secondary traits and tertiary metrics would perhaps be best solicited from individuals more attune to the complexities and intricacies of combat vehicle design. Without full appreciation for the dynamic interactions at even the principal level, there is the very real potential to misdirect real resources and pursue insufficient strategies not conducive with appropriately considered fighting vehicles.

Regarding decision making tools, respondents in both groups indicated a desire to see the progression of data distillation. In other words, they wanted to have the raw data of each candidate available, and see the successive operations done to normalize and subsequently weight and rank it accordingly. Efforts to make a two and three-dimensional depiction of the candidates represented by axes for survivability, lethality, and mobility attributes were not well received. However, the one dimensional bar chart depiction illustrated in Figure 28, received higher affinity and appeared to add some value with respect to group consensus in the decision making process as will be explained in greater depth in the next section.

3.6 Candidate Vehicle Selections

Based on the weighting data, for either an individual or a group, the 6 candidate vehicles can be ranked relative to their quantitative scoring using a decision matrix software program. This ranking, again for either an individual or a group, can be compared against the overt candidate vehicle choice rankings. This section includes analysis on the candidate vehicle rankings derived from weighting and choosing methods.

3.6.1 Vehicle Ranking Based on Weighting Using DECMAT

To assist in the quantitative analysis of courses of action (COAs) developed as part of the military decision making process (MDMP), the U.S. Army Command and General Staff College (CGSC) directed the development an AHP-based decision matrix software program called DECMAT. This program can process both relative value and raw data (multiplication) matrices in order to calculate the best candidate in a set given an established set of criteria weights and an array of evaluation criteria. When the principal attribute weights generated by the cumulative group-data (Table 25) as well as the candidate vehicle specification data (Table 23) were placed into DECMAT, candidate vehicles were ranked in the following order: C (high survivability, tracked), F (high survivability wheeled), A (high lethality, tracked), D (high lethality, wheeled), B (high mobility, tracked), and E (high mobility, wheeled).

3.6.1.1 DECMAT's Algorithm

DECMAT uses either a relative values or a multiplication matrix with weighted products to calculate this rank. The relative value score is simply the sum of products for weighting values and normalized criteria (Equation 20). In this equation, i is the candidate index, w_j is the weighting value for criteria *j*, and $\hat{c}_{ij}$ is the normalized criteria value *j* for candidate *i*.

The multiplication matrix score is calculated differently, but has the advantage of accepting dimensional values for each candidate. Using the same nomenclature as Equation 20 with the exception of c_{ij}, which is the non-normalized criteria value *j* for candidate *i*, Equation 21 is the formula used to calculate a weighted product score. More specifically, each candidate performance specification (non-normalized c_{ij}) is raised to the power of its column attribute weight, then these exponentiated values are multiplied across rows to produce a candidate score.[145] In terms of the final score, less is better. If the objective is to maximize the criteria of interest, then *w* is negative; if the objective is to minimize the metric, then w is positive (Equation 21). Before proceeding further, it may be worth stating that the underlying premise of this method is that attribute efficacy directly sums to determine a candidate's worth. Critically, synergisms and conflictions are not considered in the calculation of the best candidate in the set of options.

$$\text{score}_{\text{i}} = \prod_{j=1}^{n} w_j \hat{c}_{ij} \qquad \text{Equation 20}$$

$$\text{score}_{\text{i}} = \prod_{j=1}^{n} c_{ij}^{\,w_j}$$
$$w_j < 0, \text{if criteria j to be maximized}$$
$$w_j > 0, \text{if criteria j to be minimized} \qquad \text{Equation 21}^{146}$$

[145] Richard B. Stikkers, DECMAT, Version 2.2, 26OCT1998, no copyright, published under Borland's License Statement.
[146] Low score wins.

3.6.1.2 DECMAT Algorithm Example

An example of the weighted product method (Equation 21) is provided below. Imagine a consumer is investigating the purchase of a new truck for his ranch. He has only two criteria: purchase cost and carrying capacity. In other words, he wants a cheap truck that can carry as much as possible. Upon questioning, he rated cost as (much) more favored to capacity, therefore the weighting values assigned to cost and capacity are 3 and 1 respectively. He is considering two truck models: Alpha and Beta. Cost and performance specifications for these two vehicles follow:

Criteria [unit] Weight Desired ► / **Candidate ▼**	**Cost [$1,000]** **3.0** **Less is better**	**Load [ton]** **1.0** **More is better**
Alpha	30	2
Beta	25	1.25

The weighted product score (Equation 21) indicates that based on the decision maker's preferences and the candidates available, Beta has a lower score and is thus predicted as the better choice for the rancher's new truck.

$$\text{Alpha} = \left(30^3\right)\left(2^{-1}\right) = 1.35 \times 10^4$$

$$\underline{\underline{\text{Beta}}} = \left(25^3\right)\left(1.25^{-1}\right) = \underline{\underline{1.25 \times 10^4}}$$

3.6.1.3 Sensitivity Analysis

When applied within DECMAT, the group attribute weighting values for the principal attributes produced a vehicle rank that was used as the order of merit. Using the available software functions, a sensitivity analysis was conducted on the 3 principal attributes and 8 specification metrics (Table 23) with their respective population weighted average weighting values. Through exercising the software, it appeared that the DECMAT routine increases the weighting on each attribute one at a time. This precludes gaining insight on any interactions between attribute weightings, and it also does not appear to consider sensitivity to weighting decreases.

None of the survivability metrics (armor thickness, armor material density, and blast protection rating) were reported as sensitive to weighting, meaning that candidate C remained the top-ranked vehicle within the weighting value bounds explored for the metrics used to define survivability. Only one lethality metric (cannon kinetic energy) was sensitive to weighting. If this metric weighting was increased from 0.15 to 0.42, the top-ranked candidate switched from C to A. This is an almost 300% change in preference weighting value. Two mobility metrics were sensitive to weighting, but again at very large factor increases in weighting value. If the weighting for acceleration was increased from 0.08 to 0.51 (greater then 6 times increase in weighting required), then the top candidate shifted from C to F. And if the weighting value for the power to weight ratio was increased from 0.08 to 0.77, the top candidate shifted from C to D. Thus, a nearly order-of-magnitude increase in weighting was required to make candidate D the top ranked candidate. A summary of the sensitive metric weightings, as well as the values associated with the change, are provided in Table 27.

Table 27: DECMAT Candidate Vehicle Sensitivity Analysis

DECMAT Sensitivities ► / **Metric (Attribute) ▼**	**Original value**	**Shift-point value (factor increase)**	**Shift-point ranking candidate**
Acceleration (Mobility)	0.08	0.51 (6+)	F
Kinetic energy (Lethality)	0.15	0.42 (2+)	A
Power to weight (Mobility)	0.08	0.77 (9+)	D

Based on the cumulative group's strong weighting for survivability, and the distinct advantage possessed by candidates C and F with respect to the metrics used to contribute to candidate survivability, i.e., armor material density, blast protection rating, armor thickness, the candidate vehicle rank order was fairly insensitive to even very large factor increases in either lethality or mobility metric weightings. While candidate F had a slight advantage in blast protection rating, candidate C had a measurable advantage in armor thickness making it rank consistently better in the decision matrix results.

Somewhat surprisingly, weighting values varied significantly among individual respondents, but collectively both groups converged on commensurate values for survivability, lethality, and mobility. While the convergence demonstrates consensus, it is not an overt indicator of weighting validation or candidate quality. In other words, the consensus on weighting values does not, in itself, indicate that a selection based on these weighting values would produce a candidate with greater performance than any other in the set of options.

3.6.2 Individuals as "Choosers"

In Group 1, 5 individuals (21%) overtly chose candidate C as the best, while in Group 2, 13 individuals (62%) chose candidate C. Group 2 had 40% more respondents choose DECMAT's best vehicle, while in Group 1, 4 individuals (17%) correctly chose one of DECMAT's top two candidates. In gaming parlance, e.g., horseracing, this is known as an "exacta". In Group 2, 7 individuals (33%) earned exactas. In both Group 1 and Group 2, three individuals ranked their overt candidate selection for the top three vehicles in the same order as DECMAT (12% and 14% respectively). In gaming parlance, this is known as a "trifecta". A strikingly large number of individuals chose either candidate C or F (combination) as their best candidate: 54% and 76% respectively. These results for raw scores and as fractions of the population are provided in Table 28.

Table 28: DECMAT's Winners, Exactas, Trifectas, and Top 2 Choices for Group 1 and Group 2

DECMAT's rankings ► / **Respondents ▼**	**"Winners" C %**	**"Extactas" C, F %**	**"Trifectas" C, F, A %**	**"Top 2" C and F %**
Group 1 N = 24	5 21%	4 17%	3 12%	13 54%
Group 2 N = 21	13 62%	7 33%	3 14%	16 76%
Random Guess Probability	17%	3.3%	0.83%	33%

The probability of simply guessing the correct order for the top three vehicles, e.g., getting a trifecta, is one in 120 (0.83%), while the probability of guessing the correct order of the entire set of candidates is one in 720 (0.14%). Equation 22 calculates the number of permutations of *r* objects chosen from *n* objects: P(n,r). So the probability of choosing a trifecta is calculated using $1/\,{}_6P_3$, and that of choosing a perfect order is $1/{}_6P_6$.

$$P(n,r) = {}_nP_r = \frac{n!}{(n-r)!} \qquad \text{Equation 22}$$

Examining the survey responses through the "lens" of probability is informative, especially if one assumes that individuals in both groups were equally skillful in identifying the more preferable ground combat vehicle candidates. For example, participants in Group 2 were 3 times as likely to choose the DECMAT "winner" C (62%) than participants in Group 1 (21%) who, as a group, chose C only slightly more often than would be expected by random chance (17%). Group 1's selections demonstrate that the choice of C was not obvious from the raw data. That said, individuals in both groups bested random chance (33%) to choose one of DECMAT's "Top 2" C and F as their top choice: Group 1, 54%; Group 2, 76%. Group 1 selections demonstrate that the superiority of C or F was somewhat obvious based on the raw data, but clearly not as obvious as it was to Group 2 respondents.

At the same time, the statistical rarity of trifectas (0.83% or 1 out of 120 probability) permits some interesting inferences from the data. Trifectas, which require skill and insight, occurred equally often in both groups, supporting the claims that 1) the two groups were about equally skilled with respect to ground combat vehicle selection choosing {C, F, A} over 15 times more often than would be expected merely by chance, and 2) the format(s) for the data presentation did not significantly aid (or hinder) the ability of certain, perhaps particularly skilled/insightful, individuals to identify “superior” fighting vehicle candidates.

The story is somewhat different in the case of exactas (3.3% or 1 out of 30 probability) on which the two groups diverge. While it has already been noted that many individuals in both groups were able to identify C and F as superior ground combat vehicle candidates, Group 2 participants were twice as likely as Group 1 participants to choose exactas (33% versus 17%), but both groups much more often than expected by mere chance. Group 2’s relative performance advantage over Group 1’s in choosing the “Top 2” (2% versus 21%) 7), exactas (33% versus 17%), and winners (62% versus 21%) directly reflects the influence of the data presentation format, namely the decision support tools (Table 24, Figure 28 and Figure 29) promoted consensus and directed—for good or potentially for bad—the decision making.

3.6.3 Individual and Group Consistency with Respect to Choosing and Weighting

Each respondent was assessed an internal consistency (IC) rating that measured the mean square error between the respondent’s personal weighting choice from the survey and their overt vehicle choice (Equation 23), i.e., a statistical measure of deviation between their outright selection and their stated desires. The subscript *wt* stands for weighting, i.e., rank derived from attribute weights, while the subscript *ch* stands for choosing, i.e., rank attributed to overt choice. The variable N is the number of candidates under consideration. The vehicle choice by personal weighting is the vehicle ranking that would have been selected if the respondent’s weightings were used with no further consultation with the respondent. In other words, the candidate rankings were calculated based on the logic and insight reflected or embodied in the attribute weightings as applied to the set of candidates.

$$IC_i = \sqrt{\frac{\sum_{j=A}^{F}\left(j_{rank_{\mathrm{i,wt}}} - j_{rank_{\mathrm{i,ch}}}\right)^2}{N-1}} \qquad \text{Equation 23}$$

Each survey respondent was also assessed on their external consistency between two standards: the first, *EC1*, measured the mean square error between the group's collective attribute weighting choice and a respondent's personal overt choice (Equation 24); the second, *EC2*, measured the mean square error between the group's collective attribute weighting choice and a respondent's personal weighting choice (Equation 25). The collective group is defined as the group of respondents. As there were two main groups of respondents, an individual is compared against his particular response group. The variable *j* is an index for the six candidate vehicles A–F. The subscript *pop* is the average for the collective population, while *i* represents an individual respondent. So for these equations, the population is the respective group of respondents, i.e., the collective group. The group's vehicle selection can simply be considered a popularity vote, where each of the 6 candidate vehicles was ranked according to collective scores.

$$EC1_i = \sqrt{\frac{\sum_{j=A}^{F}\left(j_{rank_{\mathrm{pop,wt}}} - j_{rank_{\mathrm{i,ch}}}\right)^2}{N-1}} \qquad \text{Equation 24}$$

$$EC2_i = \sqrt{\frac{\sum_{j=A}^{F}\left(j_{rank_{\mathrm{pop,wt}}} - j_{rank_{\mathrm{i,wt}}}\right)^2}{N-1}} \qquad \text{Equation 25}$$

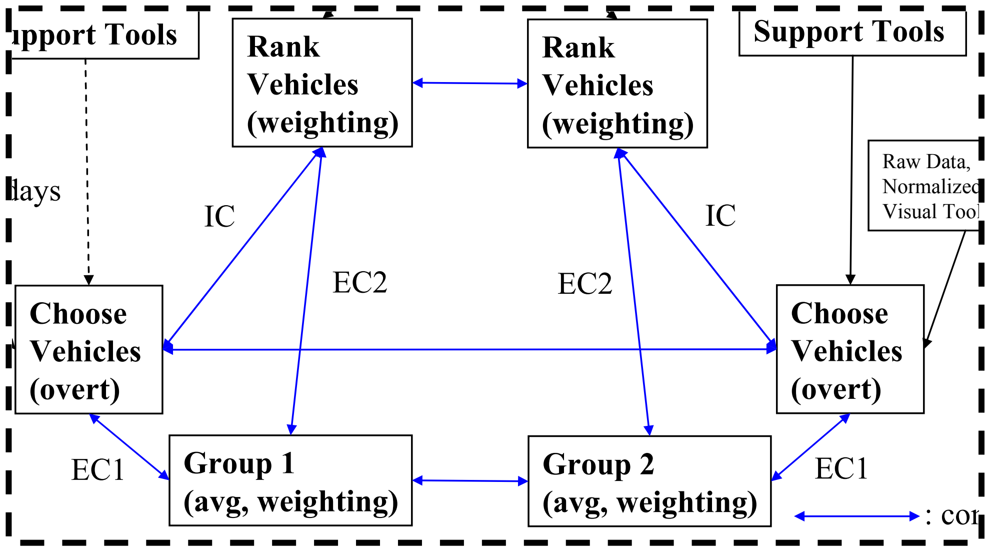


Figure 34: Cropped portion of Figure 27, i.e., investigation methodology. The consistency terms are depicted with respect to the comparative elements used for each type.

These metrics, *IC*, *EC1*, and *EC2* were created by the author in order to quantify the consistency between an individual's weightings and selection, as well as compare those values with respect to the group's weightings. In other words, these metrics serve as an indicator of how stable an individual's rankings were when compared against their own weighting and the group weighting. Since this is an active area of interest to behavioral economists, i.e., the linkage between the logical and illogical decisions made by consumers, similar metrics may appear in those contexts. Therefore, these heuristics seemed an appropriate measure of the respondent's level of consistency by comparing their weighted choice to their overt choice.

When considering the group averages for internal and external consistency, the second group was more consistent, i.e., it had lower average values for *IC, EC1,* and *EC2* (Table 29). The major differences between the surveying of the two groups were the (1) time between weighting and choosing solicitation and (2) the decision support tools presented to the second group.

Table 29: Internal and External Consistency Averages

	IC_{avg}	$EC1_{avg}$	$EC2_{avg}$
Group 1 N = 24	2.2	2.1	0.9
Group 2 N = 21	1.5	1.6	0.2

Group 2 was more consistent than Group 1 for all measures, perhaps due to the decision support tools that embodied the generally accepted ground combat vehicle value system of survivability, lethality, and mobility. Also, for both groups, most individuals had a weighting derived candidate rank that closely matched the group weighting derived candidate rank, as depicted with the metric *EC2*. This value was so low for Group 2 because most individuals appear to have relied on the decision support tools (namely Figure 28) which embodied the collective value system and associated weightings. These observations provide further evidence of the consensus building and directing of the decision making afforded by the decision support tools.

The respondent data was further analyzed to see if there was any correlation between individuals that could be described as “skilled choosers” and “adept weighters”. A good chooser was someone whose overt vehicle choice converged closer to the group’s collective weights that produced the DECMAT hierarchy ranking of the vehicles. A good chooser had a low value for *EC1*. A good weighter was categorized as someone who had a low value for *EC2*, i.e., their individual weighting converged closely to the correct ranking of the vehicles for the group’s collective weights. Looking at both groups, those individuals that ranked in the top five for *EC1* typically ranked in the top five for *EC2* indicating there was a positive correlation between assessing weights and selecting vehicles (note: three of the top five in each group chose trifectas). It also appeared that the majority of good weighters and good choosers (7 of 10 individuals) were from the maneuver branches (armor, infantry, aviation) of the Maneuver, Fires and Effects divisional areas, formerly known as combat arms branches in the U.S. Army.[147]

3.6.3.1 Illustration and Interpretation of Consistency Calculations

An example is now presented to demonstrate the method used to calculate a respondent's internal consistency of weighting and choosing (*IC*), external consistency with respect to his overt choice as well as his collective group's weighted choice for vehicle ranking and (*EC1*), and his external consistency with respect to his weighted choice and his group's collective weighted choice for vehicle ranking (*EC2*).

We revisit the rancher scenario, this time where a group of ranchers are considering the purchase of a replacement truck given three choices, Alpha, Beta, and a new model Gamma (§ 3.6.1). In this case, we will also assume a group of respondents has provided criteria weighting preference, which if used in conjunction with a pairwise comparison matrix and a decision support software title like DECMAT, produce a vehicle ranking of Beta (#1), Alpha (#2), and Gamma (#3). Additionally, when this same notional collective group use any/all means available to rank the three candidates, they respond with a like ranking of Beta (#1) and Alpha (#2), and Gamma (#3).

Two individuals provide weightings which can be used to derive a vehicle ranking unique to their values as depicted in Table 30. Additionally, when asked to overtly

[147] Of the top five in both groups (10 individuals), only three were from basic branches other than combat arms. And of those three, one was branch detailed armor (a combat arms branch).

choose the vehicles, each individual generates a ranking unique to their preferences as depicted in Table 30.

Table 30: Alpha, Beta, and Gamma Truck Selection Example

	Weighting			Overt		
	#1	**#2**	**#3**	**#1**	**#2**	**#3**
Individual 1	Beta	Alpha	Gamma	Gamma	Beta	Alpha
Individual 2	Gamma	Alpha	Beta	Beta	Alpha	Gamma
Group	Beta	Alpha	Gamma	n/a	n/a	n/a

Individual 1's consistencies are calculated:

$$IC_1 = \sqrt{\frac{\sum_{j=Alpha}^{Gamma}\left(j_{rank_{i,wt}} - j_{rank_{i,ch}}\right)^2}{N-1}} = \sqrt{\frac{(2-3)^2+(1-2)^2+(3-1)^2}{3-1}} = 1.7$$

$$EC1_1 = \sqrt{\frac{\sum_{j=Alpha}^{Gamma}\left(j_{rank_{pop,wt}} - j_{rank_{i,ch}}\right)^2}{N-1}} = \sqrt{\frac{(2-3)^2+(1-2)^2+(3-1)^2}{3-1}} = 1.7$$

$$EC2_1 = \sqrt{\frac{\sum_{j=Alpha}^{Gamma}\left(j_{rank_{pop,wt}} - j_{rank_{i,wt}}\right)^2}{N-1}} = \sqrt{\frac{(2-2)^2+(1-1)^2+(3-3)^2}{3-1}} = 0.0$$

While individual 2's consistencies are calculated:

$$IC_2 = \sqrt{\frac{\sum_{j=Alpha}^{Gamma}\left(j_{rank_{i,wt}} - j_{rank_{i,ch}}\right)^2}{N-1}} = \sqrt{\frac{(2-2)^2+(3-1)^2+(1-3)^2}{3-1}} = 2.0$$

$$EC1_2 = \sqrt{\frac{\sum_{j=Alpha}^{Gamma}\left(j_{rank_{pop,wt}} - j_{rank_{i,ch}}\right)^2}{N-1}} = \sqrt{\frac{(2-2)^2+(1-1)^2+(3-3)^2}{3-1}} = 0.0$$

$$EC2_2 = \sqrt{\frac{\sum_{j=Alpha}^{Gamma}\left(j_{rank_{\text{pop,wt}}} - j_{rank_{\text{i,wt}}}\right)^2}{N-1}} = \sqrt{\frac{(2-2)^2 + (1-3)^2 + (3-1)^2}{3-1}} = 2.0$$

In this example, we may say that the first individual was more internally consistent, since he chose vehicles in concert with his weighting-based choice; in other words, his *IC* value was better ($IC_1 < IC_2$). We may also say that the second individual chose more consistently with respect to the group's weighted-ranking ($EC1_2 < EC1_1$). Finally, we can say that the first individual weighted more consistently with the group ($EC2_1 < EC1_2$). In fact, the first individual's weighted choice matched the group's weighted choice perfectly, i.e., $EC2_1 = 0$. Given more individuals, weighting criteria, and potential candidates available for selection, the distinction between, as well as the insight gained, from using these measures of consistency becomes more apparent than in this simple illustrative example of only two individuals and three candidates. However, the basic procedure used to calculate these values remains the same.

3.6.4 Group Attribute Weighting and Candidate Vehicle Selection

Figure 35 illustrates the candidate vehicles rank-ordered according to the two group's attribute weighting and overt choosing. In the figure, the group's candidate ranking from 1 to 6 is presented as a column. On the outside (columns 1 and 4) is the order derived from the group attribute weighting average, and on the inside (columns 2 and 3) is the order calculated from the group ranking tally. Even in the absence of a decision support tool and after 10-days delay between the attribute weighting survey and an overt vehicle selection choice using raw data only (Table 23), Group 1 did a "good" job, i.e., good is defined as consistent with the DECMAT score, of overtly choosing a candidate. As a group, they chose F (or the second ranked candidate) over C (or DECMAT's top scoring candidate); 54% chose either C or F as their top candidate. As this group's ranking order was further analyzed, Group 1 was somewhat inconsistent with respect to order regarding weighting-derived candidate versus overt vehicle choice. Also, Group 1 ranked vehicle D second, demonstrating an apparent focus on the wheeled configurations versus performance specifications as both F and D were wheeled variants. Based on Group 1's selections, it appears that the more detailed candidate vehicle data without contextual reference (relative with respect to top performer, dimensional with respect to principal attributes) led to inconsistent choices and possible fixation on distinct, less relevant candidate specifications.

Given a possible advantage of having an attribute-focused survey in temporal proximity to the overt vehicle selection exercise, as well as a visual decision support too (bar graph) that packages the relevant vehicle engineering data in a directly additive fashion that clearly identifies what may be considered the *best candidate*, Group 2 appeared more consistent with respect to weighting and choosing. In the preceding sentence, "best candidate" is italicized because again, the fundamental premise of a directly additive scoring method is that attributes contribute in an additive fashion toward candidate worth, and critically there is no synergy or conflicting interactions among attributes.

Regarding the improved consistency, Figure 35 illustrates this trend. Group 2 chose an order closer to their weighting preference than the first group did. More specifically, while the first group had three candidate vehicles move up in rank, and three candidate vehicles move down in rank, with respect to weighting rank and choosing rank. The second group had just a single swap of rank. This figure also demonstrates how consistent the weighting selections were between Group 1 and Group 2.

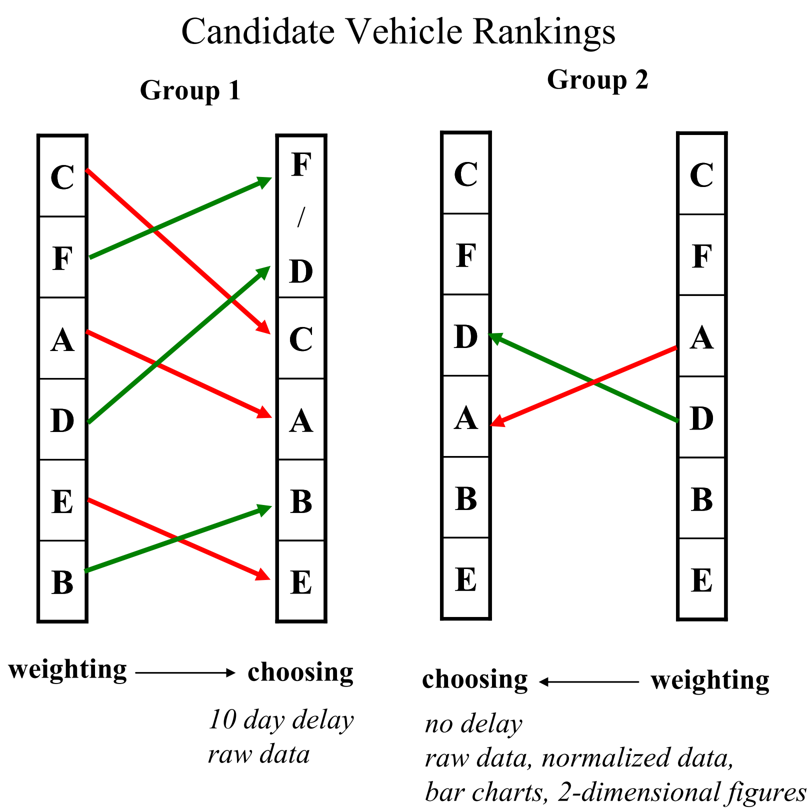


Figure 35: Rank ordered candidate vehicles A–F rank, as derived from group averaged attribute weighting and group averaged ranking scores. A green arrow indicates an increase in ranking from group weighting to group choosing, a red arrow indicates a decrease in ranking. In Group 1, vehicles F and D were tied in overt choice.

3.7 Effects of Decision Support Tools on Candidate Vehicle Selection

Based on Group 2's overt candidate vehicle selection results, the presentation of the raw performance specification data (Table 23), subsequently normalized with respect to the top performer in each field (Table 24), and then visually depicted in both a bar chart (Figure 28) and two-attribute comparison graphs (Figure 29) created better internal consistency (lower IC) and higher group consensus (lower EC1 and EC2).

The bar chart depiction of vehicle worth ranked best in an ordinal assessment of weighting tools and visual aids with Group 2 with over 58% of those surveyed scoring the bar chart first or second (out of 4 forms of data) in preference. In terms of data presentation preference, the bar chart was followed in order of preference by the normalized specification data of candidate vehicles and then simply the raw data. Based on the affinity for the bar chart, as well as its similarity to the histogram of the overt candidate selections, it appeared that respondents may have simply relied on the height of the bar for the corresponding candidate vehicle and ranked them according to the chart. To test this hypothesis, the Pearson correlations between attribute bar length (Figure 28) and overt choices (Figure 36) were computed. These very strong correlations lend credence to the argument that Group 2 may have relied heavily on the graphical representations made to them, thus sounding a cautionary role for would-be data suppliers and surveyors. The statistical correlation between candidate vehicle (or attribute bar height) and overt choice was very strong with a value of 0.98, as was the correlation between just the survivability portion of the candidate vehicle bar and selection (0.93) and the survivability-lethality portion (0.97). Notably, there were no significant correlations observed for Group 1, and the other correlations for Group 2 were weak to moderate (Table 31).

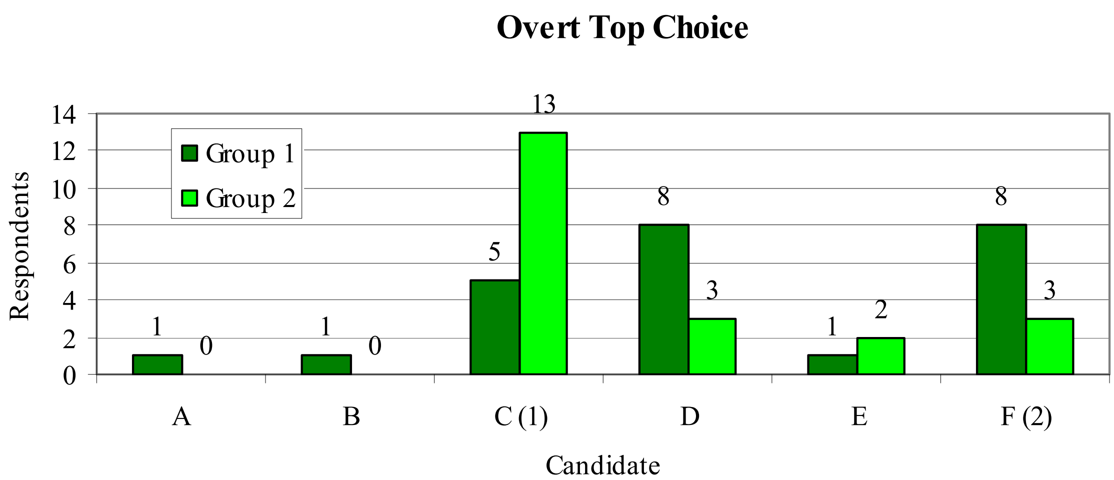


Figure 36: Overt top choice histogram. The first and second ranked vehicle candidates from DECMAT scoring methods, i.e., C and F, are labeled parenthetically. The populations for Group 1 and Group 2 are N = 24 and N = 21 respectively.

Table 31: Pearson Correlations Between Attribute Bar Length and Overt Choice[148]

Group \ **Attribute(s)**	**S**	**L**	**M**	**SL**	**SM**	**LM**	**SLM**
Group 1	0.46	0.08	0.1	0.47	0.53	0.16	0.58
Group 2	0.93	0.20	-0.40	0.97	0.86	-0.10	0.98

148 Correlations considered strong (> 0.9) are highlighted in green.

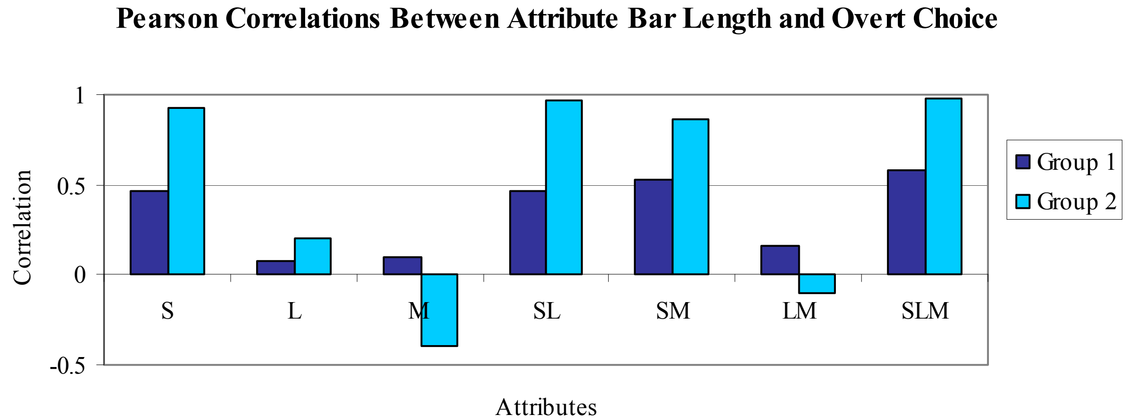


Figure 37: Pearson correlations between attribute bar length and overt choice. By relative magnitude for each group, Groups 1 and 2 demonstrated similar affinity for the attributes (single and in combination) of S, L, SL, SM, and SLM, with the difference being an amplification in relative correlation magnitude for Group 2.

While 54% of Group 1 ranked vehicles C or F as their top choice, 80% of Group 2 ranked vehicles C or F as their top choice (Figure 36). It should be noted that in both cases, the two groups produced principal attribute weighting values that generated virtually the same preferential order (albeit B and E are swapped indicating slightly greater mobility preference from Group 1). However, the Group 1 deviated from this order in overt selection, notably in the absence of decision support tools that may have reinforced this weighting in a visual manner. When analyzing Figure 37 by relative magnitude, Groups 1 and 2 demonstrate a similar affinity for most attributes, notably survivability, lethality, and the combinations of survivability-lethality, survivability-mobility, and survivability-lethality-mobility. The main difference is that the stronger correlation observed for Group 2 illustrates the amplification of the response attributed to the alternative decision support tools afforded to them during their overt selection. That said, both groups appear to have shared a similar value system with respect to the principal attributes.

Even though there were no strong correlations for Group 1, the composite interpretation of survivability, lethality, and mobility (SLM) was ordinally ranked first in correlation value for both Group 1 and Group 2. This demonstrates a proclivity for both groups to choose candidates in accordance with these attributes, even in the absence of a decision support tool designed explicitly to present the engineering data in a method amenable to direct interpretation. In other words, a fraction of Group 1 was still able to divine from the raw data the underlying candidate merit through the composite lens of survivability, lethality, and mobility. Finally, since Group 2 showed such a strong correlation with the chart and the overt selection, this strongly suggests that a number of respondents based their overt decisions on this tool.

Regarding the vehicle configuration, i.e., wheels versus tracks, Groups 1 and 2 indicated some preference for wheeled over tracked candidates. Group 1 overtly chose 71% of their top candidates as wheeled variants, while Group 2 only chose 38% of their top candidates as wheeled, due to the remaining 62% being awarded to candidate C (a tracked vehicle) as driven by the bar chart. The vehicle configuration had no explicit contribution toward the calculation of a candidate vehicle score, which was based purely on technical specifications, but this wheels-versus-tracks specification—one which holds strong contextual merit among some decision makers—may have led some to discount tracked candidates in favor of wheels, or vice versa.

It can be conjectured that, given this freedom to choose, the bar chart depiction of candidate vehicle survivability, lethality, and mobility at least encouraged the respondent to resolve an advantage with respect to one attribute with an apparent weakness in another. Done in a more visual way, as opposed to a numeral in a table or matrix, the bar chart *may* have kept the decision maker visually and cognitively apprised of the relative attribute merit of each prospective candidate vehicle with respect to the set. In any case, regardless of the way the information was presented, both groups were free to choose the final ranking in whichever manner or order they desired or felt appropriate.

3.7.1 Potential Perils and Pitfalls of Decision Support Tools

These observations demonstrate the implicit dangers associated with the methods pursued in this chapter. Since a fundamental premise of AHP is that the qualities of candidates are simply additive, not conflicting, and contribute positively toward the desired objective, the scalar magnitude of the bar chart can potentially misinform a decision maker if it does not reflect the true efficacy of a candidate vehicle. This implicit assumption that the AHP function totally defines the design space may even be interpreted as demonstrating an incredible amount of hubris and prescience with regard to ground combat vehicle design and eventual usage. This makes the methods and data presentation susceptible to failed additive logic. Blind faith in a method like AHP or the data presented may yield a false sense of confidence with the decision and outcome.

If the candidate qualities are not simply additive, if there are conflictions between attributes, and if the attributes do not contribute positively, i.e., “more is not better”, toward vehicle performance, then this method could lead design and decision efforts down a fruitless path. Any error in these assumptions, especially in light of how persuasive the bar chart appears to have been toward decision maker overt candidate vehicle choice, could sway a group toward a suboptimal candidate, one plagued with attribute conflictions and negative interactions not captured or fully considered in the evaluation of available options. This could substantially misdirect developmental efforts, while wasting time and money, valuable commodities made more so by the challenges present in the contemporary operating environment.

3.8 Lessons Learned

- The way in which information was presented affected candidate vehicle selection. When comparing weighting-derived versus overtly-chosen vehicle selection, the inclusion of a nondimensional visual depiction of combat vehicle specification data as related to the principal attributes of survivability, lethality, and mobility was found to improve the consistency and apparent quality of choice from a set of candidate platforms. Conversely, raw data left in absolute terms and not linked to an attribute reduced consistency and may have encouraged respondents to focus on singular metrics or the vehicle configuration itself.
- The data presentation method made a difference in overt candidate vehicle selections. In the most preferred form, i.e., the bar chart representation, the visual depiction of survivability, lethality, and mobility correlated strongly with decision maker overt choice. The strong correlation can provide benefit for consensus building and for collapsing complex data into a simpler form. However, it can also present misleading conclusions without proper validation of weighting values and candidate efficacy.
- Weighting values varied significantly among individual respondents, but collectively both groups converged on commensurate values for survivability, lethality, and mobility. While the convergence demonstrates consensus, it is not an overt indicator of weighting validation or candidate quality.
- In the format pursued for these decision support tools, the packaging of specification data with respect to survivability, lethality, and mobility assumed an additive relationship between the criteria. Given the dynamic interactions between combat vehicle attributes, this may be an ineffective method of guiding a selection effort. In other words, the strength of a weighting value is dependent on validation of its contribution to a performance metric. Without contextual understanding of the significance of weighting values or the relationships between attributes, the numeric or scalar depicted superlative may not be the best choice. This is a warning to both analyst and decision maker alike as to the limitations of using this method to guide a decision making effort.

3.9 Conclusions

The work in Chapter 3 demonstrated that decision support tools built around the principal attributes of survivability, lethality, and mobility can significantly improve the consistency of group selection of a ground combat vehicle. The improvements came from greater consistency between decision-maker attribute preference and the related levels of those attributes in candidate vehicles. Given that ground combat vehicles are primarily designed to be a mobile and protected source of firepower, it was logical to build an organizational framework around the principal attributes of survivability, lethality, and mobility, and then to place metrics appropriately beneath those attributes. As most decision support tools increase dimensions for candidate evaluation and rely on relative value comparisons, both techniques were employed in the comparison matrix creation and visual aids provided to respondents.

A prerequisite for this effort was the collection of weighting data for the calculation and subsequent visualization of candidate vehicle performance specifications. Once the framework and weighting values were established, the amalgamation of performance specifications lent itself to any visual depiction consistent with the survivability, lethality, and mobility construct. Respondents expressed preference for the bar chart depiction of relative candidate levels of each principal attribute. Use of this visual interpretation of performance data highly correlated to more consistent ranking selection to the extent it appears that respondents relied heavily on it.

A source of vulnerability in any decision making pursuit is the elusiveness of data to validate the decision quality. The inherent uncertainty in many pursuits, as well as the inability to forecast how alternative abandoned candidate selections may have fared, make it difficult to evaluate decision quality. In the absence of a definitive validation of weighting values, decision-maker and engineer can simply be consistently wrong in the pursuit of what is believed to be an effective combat vehicle. To use a marksmanship analogy, the tools used helped to "tighten the shot group" or reduce the difference between weighting-derived and overtly-chosen vehicle selection. However, a subsequent effort is necessary to see if the shots are "on target", i.e., is the candidate selection rank order validated by some simulation effort or practical demonstration exercise. Alternatively, a preceding effort aimed at investigating the relative value and parametric relationships between survivability, lethality, and mobility would do more to aid decision makers since information of this sort could contribute "further up stream" in the decision process. In other words, a deeper appreciation for the attribute interactions and correlations with platform performance could guide the creation of options versus simply being used to choose better among a finite set of candidates. From a design perspective, insight gained on the relative contribution and interaction of each attribute might be used to direct performance metrics.

In conclusion, the high art of decision making is not simply choosing among alternatives, but to foster an environment conducive with generating previously unconsidered alternatives. In the next chapter, a survivability, lethality, and mobility framework will be used to evaluate the relative contribution of the principal attributes on the performance of a prototypic combat vehicle. In doing so, the respondent weighting data produced in Chapter 3 can be compared with the relative attribute contribution toward creating a winning fighting vehicle in a simulated combat environment.

Chapter 4: Performance Effects and Attribute Interactions of Survivability, Lethality, and Mobility

> Again, it is possible to fail in many ways, while to succeed is possible in only one way… excess and defect are characteristics of vice, and the mean of virtue… for men are good in but one way, but bad in many.
>
> —*Aristotle, Nichomachean Ethics*

> Theory guides, experiment decides.
>
> —*I.M. Kolthoff*

4.1 Introduction

A set of prototypic ground combat vehicles, each with methodically prescribed levels of survivability, lethality, and mobility, were designed and subsequently fought by ROTC cadet volunteers in a physics-based, simulated combat environment. The results of each mission were analyzed to investigate the relative effects and coupled interactions between the combat vehicle principal attributes in relation to a series of performance metrics. The results from the simulations demonstrated that the principal attributes do not appear to contribute to platform efficacy in a simply additive fashion. Rather, in some cases, a surprising result was observed, i.e., mission performance actually dropped with greater relative levels of an attribute. The findings indicate that it may not be advisable to prescribe vehicle requirements without first performing some simulations or at least thoroughly considering the net effect and interactions of the principal attributes with respect to combat system performance. This practice may be referred to as performance-based design, or the concept of pursuing attributes with a concerted and cognizant focus toward holistic platform performance.

4.2 Background

In light of the attribute weighting values solicited from respondents and described in Chapter 3, the U.S. Army officers who participated in the survey exercises were clearly focused on survivability as the dominant principal attribute. However, one must question the value of such weighting values in the absence of contextual validation of the relative contributions and interactions (conflictions and synergisms) between survivability, lethality, and mobility with respect to ground combat vehicle performance. In Ogorkiewicz's treatise on the evaluation of tank designs, this respected combat vehicle designer provides a strongly worded caution regarding the potential errors in comparing alternative platform designs by considering only the performance metrics.[149] In a complaint echoing Bekker's disdain for the use of the term "mobility", Ogorkiewicz goes on to criticize the lack of specificity when dealing with many of these terms. He goes on further to explain how these attributes and metrics can be inconsequential measurements for consideration if not deliberately linked in some way to overall platform performance. The cautionary note struck by Ogorkiewicz provided the impetus for the research question and related work contained in this chapter. Here, the research question is: **What are the relative contributions and interactions of survivability, lethality, and mobility to ground combat vehicle performance?** This question deals with investigating a method to identify, in a simulated environment, for example—the relative contributions/effects and possible coupling between attribute levels and combat vehicle platform performance.

There is a complex, dynamic interaction between principal attributes at the platform level and their net effect on system performance. Intuitively, one can sense that

[149] R.M. Ogorkiewicz, *Design and Development of Fighting Vehicles*. (New York: Doubleday and Company, 1968) 132-139.

excessive levels of survivability can handicap mobility and reduce the ability to move and engage targets, i.e., reduce lethality. Also, for a fixed vehicle mass budget, platform volume, and per-unit (vehicle) cost, redistributing respective fractions between the equipment primarily dedicated to each principal attribute may, and most likely will, affect vehicle performance metrics.

Since combat vehicles serve as an extension and amplifier of its crewmembers' capacity to complete their mission, it may be instructive to first consider the principal attributes as they might pertain at the individual soldier level. Imagine an individual is preparing to enter a room to combat a threat lurking inside. In preparation for this task, the individual is given an assortment of body armor and weapons from which to choose. Most individuals would try to find an appropriate, perhaps dynamic, balance between protecting himself (survivability), arming himself (lethality), and maintaining the ability to move about as freely as possible (mobility). This would probably be done iteratively in a *don gear – test – change gear – test* fashion, until the individual was satisfied with the capabilities and kit he had assumed on his person. With too much body armor, an individual becomes an ineffective fighter—a target to the threat if you will. With an abundance of weaponry, the fighter may also become bogged down by weight and would likely yield some (potentially considerable) ability to move under the load of so much armament. A capable fighter relies on some semblance of balance among the principal attributes of survivability, lethality, and mobility in order to equip himself in an effective fashion, thereby increasing his odds of defeating the threat and surviving the engagement.

For a combat platform crew, the dynamics are similar, but the option of shedding or assuming desired levels of survivability, lethality, and mobility are far more restrictive as they are largely established in a prescriptive fashion by the requirements generated and specified by the ground combat vehicle designer. In other words, the settings and thresholds for protection, firepower, and movement are largely fixed.[150]

A combat vehicle in the conceptual or deliberate design phase has many imposed "budgets", e.g., mass, volume, cost, and schedule. The relative efficacy of the platform, as measured by success in combat, is a function of the relative worth of the attribute level in comparison to the performance achieved within each budgetary limit. Ground combat systems fought by a crew of trained operators harnesses that capability for discretionary use of the commander. Regarding the elusiveness of elucidating the dynamic interactions, the absence of distinct relationships among these characteristics precludes objective analysis using simply attributes, traits and metrics. It also represents the greatest criticism of earlier efforts to quantify ground combat system "net worth" among candidates.[151]

In contemporary efforts, the significance of these platform attributes remains a relevant, critical, and timely subject. In a 2010 briefing at the Institute for Advanced Technology, the Commander of the Army's Research, Development, and Engineering Command (RDECOM) discussed the value of pursuing balance among mobility, survivability, and lethality in the pursuit of the next ground combat vehicle.[152] The term "balance" was not discussed further, but may refer to the performance achieved for metrics related to these attributes. It may also refer to the mass, volume, or financial budget dedicated to subsystems and functions directly related to the principal attributes. To paraphrase Aristotle, good fighting vehicles all share the capacity to provide crewmembers with a mobile, protected source of firepower, while bad fighting vehicles

[150] Some vehicles have modular armor packages that can be added on based on the enemy situation and mission profile.
[151] R.M Ogorkiewicz, *Design and Development of Fighting Vehicles,* (New York: Doubleday and Company, 1968) 132-139.
[152] Briefing given by Major General Nickolas G. Justice, Commander, Research and Development Engineering Command (RDECOM) to the Senior Service Fellow Program at the Institute for Advanced Technology, Austin, Texas, on April 28, 2010.

have unique shortcomings in one or more areas, e.g., poor mobility, inadequate survivability, ineffective lethality, etc. The legacy systems, e.g., Abrams tank, Bradley IFV, appear retrospectively to have brought a balance of principal attributes to the battlefield. Even considering initial shortcomings related to these platforms, the evolved, balanced performance specifications illuminate prior decision maker efforts focused on the design of a vehicle possessing all the essential constituent elements of a fighting vehicle, i.e., survivability, lethality, and mobility.

In contrast, the vehicles procured in the first decade after 9/11 have been rather unbalanced, e.g., Stryker with high mobility, but low survivability and lethality, and MRAP with high survivability but low lethality and mobility.[153] As previously stated in § 1.3, the Stryker required protective upgrades to address this shortcoming. The minimal use of the first generation MRAPs in OEF directly reflects the lack of mobility afforded by these highly survivable, but oversized platforms.[154] Understanding the correlation and interaction of the attribute with its attendant effects on net platform performance is a fundamental step toward understanding how to design a balanced fighting vehicle.[155]

While the challenges and uncertainties associated with characterizing these relationships are not trivial, the potential return on successfully pursuing them—say in a physics-based simulation environment—could illuminate synergy and conflicts between attributes, as well as quantify the net contribution or amplification of an attribute level on vehicle performance. Given the complexity and dynamics of a ground combat vehicle "in action", it may be (and likely is) unreasonable to anticipate the net effect of the movement of a given tertiary metric, secondary trait, or even principal attribute may have

[153] As stated previously, the MRAP refers to a class of vehicles of various design and function.
[154] Dan Lamothe, "MRAPs To Get Upgrade for Afghanistan" *Marine Corps Times,* May 3, 2009. The MRAP program dedicated $158 million to procure advanced independent suspension systems for specific variants in an effort to improve the off-road (cross country) mobility of the vehicles.
[155] Kate Brannen, "Army Unveils New GCV Requirements" *Army Times*, November 30, 2010.

on overall system performance. That said, an exploration built around a design of experiment (DOE) framework, even in a simulated environment, could enlighten the design process for a fighting vehicle by revealing a methodology to gauge the net contribution of attributes on platform performance metrics that matter most.

Having insight into these interactions can also aid programmatic decisions, e.g., directing resources toward the most meaningful metrics, traits, and attributes. For example, in the highly unlikely scenario that a program encountered a surplus of money, time, or design space, it would be valuable to know where and how to apply it on the fighting vehicle for its best advantage.[156] But, in the more likely scenario, when forced to make a reduction in unit cost, program schedule, or performance requirements, knowledge of the contributions and interactions can literally inform the vehicle designer where to trim "fat" and where to spare "bone and muscle" in the fighting vehicle platform. Those metrics deemed less important, or even inconsequential, could be relaxed, while metrics associated with critical attributes could be defended with tangible evidence of their importance to system performance. Further, an understanding of the interactions between design parameters (a.k.a., factors) could further the theory of fighting vehicle design by providing a unified framework to pursue the influence of these attributes in a more holistic manner.

4.2.1 Methodology to Study the Relative Contributions and Interactions

The methodology developed to investigate this chapter's research question focused on exploring the relative contributions and interactions of survivability, lethality, and mobility to ground combat vehicle performance follows. A 2-level, 3-factorial DOE

[156] Some ground combat systems developed in the post Cold War era, particularly after 9/11, were required to be C-130 capable, meaning that the weight and volume of the vehicle was limited to a level such that it could be transported by the Air Force C-130 cargo aircraft.

framework was established to investigate the effect of varying survivability, lethality, and mobility (referred to as *factors* in the DOE framework) at acceptable and enhanced levels (referred to as *thresholds* or *treatments* in the DOE framework). Having adopted this framework and experimental technique, a collection of prototypic, simulated combat vehicle variants were built using the Joint Reconnaissance and Targeting System (JRATS) software, which is fully described in § 4.2.1. Vehicles were built in both tracked and wheeled configurations, all emulating representative levels of survivability, lethality, and mobility by essentially varying the armor package, the weapon system, and the power plant, respectively. The vehicles were subsequently fought in a search and destroy mission in a simulated urban environment, a mission typical of major combat operations in the COE. The collection of mission and platform performance data populated a DOE matrix. Statistical analysis, using the ANOVA F-test, was performed to determine the statistical significance (or perhaps, more aptly in the context of an exploratory exercise, distinguishability) of effects from single attributes (survivability, lethality, and mobility) and potential interactions between them. A flowchart of this methodology is depicted in Figure 38.

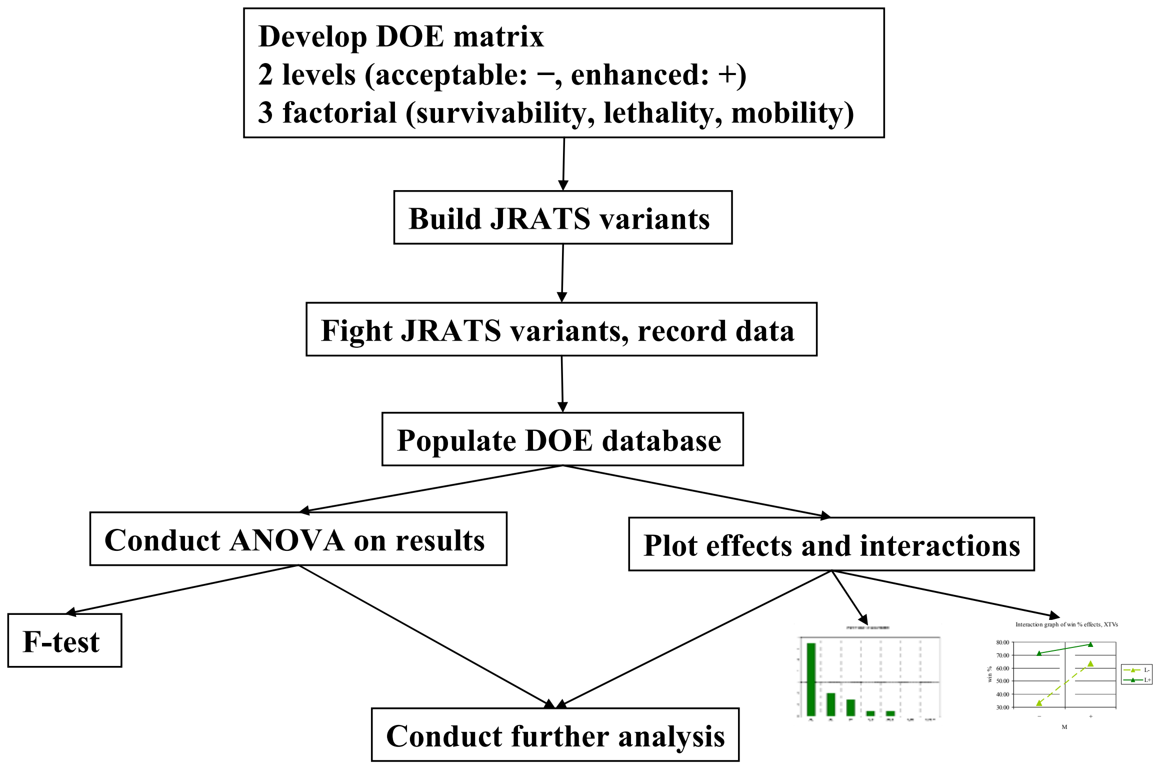


Figure 38: Flow chart for methodology designed to investigate the effects and interactions of varying levels of survivability, lethality, and mobility to ground combat vehicle performance in the JRATS simulated environment.

4.2.2 Design of Experiments (DOE) and the Analysis of Variance (ANOVA)

DOE is a "planned approach for determining cause and effect relationships."[157] As such, it was deemed an appropriate method to explore the notion of attribute thresholds on a simulated combat platform and the observed performance metrics, like– percentage of missions won (win %). By defining platform attribute levels (S for survivability, L for lethality, and M for mobility) as the "test factors", and system performance as an "effect", e.g., win %, the DOE framework is suited for an exploratory effort. The DOE methodology captures the test factor contributions on various effects, as

[157] Mark Anderson and Patrick Whitcomb, *DOE Simplified Second Edition* (Florida: CRC Press, 2007). introduction.

well as any observable interactions among them. In the absence of a definitive objective function describing the relative inputs for fighting vehicle performance, the DOE methodology can qualify and even quantify the relative effects of a collection of parameters constituting a complex, dynamic, highly coupled system like a ground combat vehicle. DOE does this more efficiently and with greater insight on possible interactions than the classic one-factor-at-a-time (OFAT) approach.[158]

The advantage of factorial design becomes more pronounced as an increased numbers of factors or variables are examined.[159] To illustrate, consider a two-level, two-factor experiment. To achieve the precision yielded by DOE in four experiments, OFAT requires six experiments. For three factors, the DOE calls for 8 runs versus 16 for OFAT. The relative efficiency of the factorial design continues to increase with every added factor, since "factorial design provides contrast of averages, thus providing statistical power to the effect estimates."[160]

Table 32: Number of Experiments Required for OFAT versus DOE

number of factors (k) at 2 levels	**OFAT**	**DOE**
2	6	4
3	16	8

As previously stated, another advantage of DOE is that it can reveal interactions of factors, often key to understanding a process (or underlying phenomenon and/or mechanism). With its ability to characterize interactions and its embedded efficiency,

[158] Mark Anderson and Patrick Whitcomb, *DOE Simplified Second Edition* (Florida: CRC Press, 2007), 41-43.
[159] Ibid.
[160] Ibid., 8-12.

DOE enables the investigator to examine a broader volume of design space and to draw inferences about a process. For this experiment, the possible interactions investigated are between the principal attributes of survivability (S), lethality (L), and mobility (M).

In some ways, the use of DOE is a paradoxical approach. To set up a meaningful experiment, the investigator should have a high level of non-statistical acumen regarding the problem. In other words, they should be very knowledgeable in the subject matter in order to choose the factors to study. Additionally, the process in question is normally of a complex nature. However, the design and analysis of the experiment, especially for an initial exploratory effort, should be kept as simple as possible. In light of these considerations (i.e., extensive knowledge coupled with great uncertainty, and observed system complexity but designed experiment simplicity) a fundamental underlying concession is that the investigator does not yet know the underpinnings of the process. The system itself is complex, else the experiment could begin from a more focused point of departure. Once an established base of knowledge is formed, iteration through confirmatory and exploratory experiments can push the complexity and insight gleaned to higher planes of understanding regarding the effects and their potential interactions.

The goal of an exploratory DOE is to "declutter" or "frame" the problem in an organized fashion to gain an understanding of the basic framing of the parameters at hand. In this specific case, the parameters of interest are the relative levels of survivability, lethality, and mobility designed into a prototypic fighting platform fought in a simulated combat mission. In recognition for his pioneering work in the field of DOE, the mathematical organization and structure of the two-factor (2^k) experiment aimed at determining the main effects and interactions of k factors at two different levels is also known as the Yate's method or Yate's standard order.[161]

[161] Frank Yates, "The Design and Analysis of Factorial Experiments" *Technical communication No. 35* Imperial Bureau of Soil and Science, Harpenden, England (1937).

Key to applying this method is adherence to building a balanced orthogonal array of experimental candidates.[162] This orthogonality can be visually appreciated when using two or three factors (Figure 39). In the context of this experimental framework, the seven degrees of freedom are: the main effects of survivability (S), lethality (L), and mobility (M); the two-factor interactions of survivability and lethality (SL), survivability and mobility (SM), and lethality and mobility (LM); and the three-factor interaction of survivability and lethality and mobility (SLM).[163] This notation for single attribute as well as attribute interactions is used in the figures accompanying this chapter.

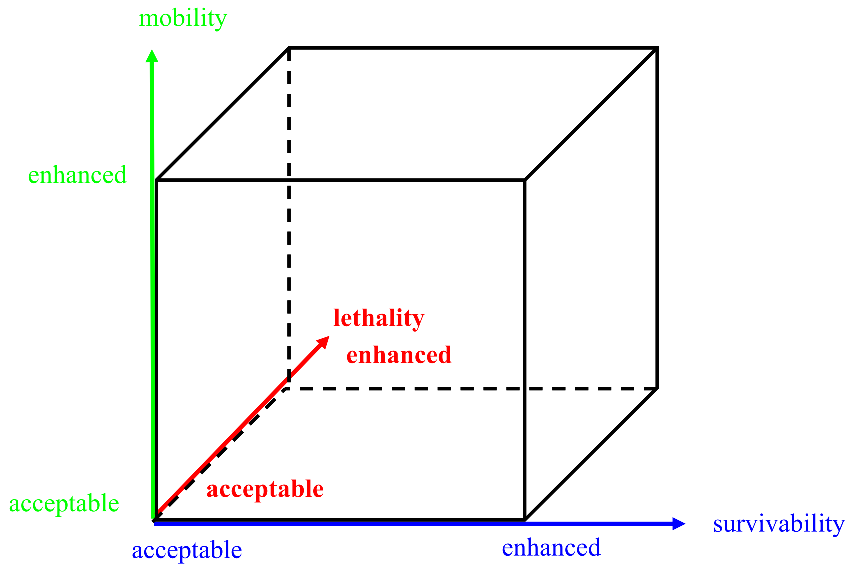


Figure 39: Two level, three factorial DOE graphical depiction for survivability, lethality, and mobility.

Given the apparent novelty of using DOE to explore ground combat vehicle design, the objective of this application was an exploration, rather than a confirmation, of the attribute effects (survivability, lethality, and mobility) on a series of global

[162] Mark Anderson and Patrick Whitcomb, *DOE Simplified Second Edition* (Florida: CRC Press, 2007) 46-59.
[163] Douglas C. Montgomery, *Design and Analysis of Experiments, Second Edition* (New York: Wiley, 1984) 267-270.

performance metrics. With the foundation for this general approach detailed by examples in DOE texts and literature, a 2^k factorial design was adopted. This form "is particularly useful in the early stages of experimental work when there are likely to be many factors investigated."[164] In a 2^k framework, *2* refers to the number of levels, established at a high and low threshold, and *k* refers to the number of factors or attributes. A 2^3 factorial experiment was examined and discussed in this chapter that investigated the survivability, lethality, and mobility attributes at acceptable and enhanced levels of efficacy on a collection of JRATS-generated prototypic combat vehicles.

4.2.3 DOE Framework Example

To illustrate Yate's standard order with three notional factors *A, B,* and *C* at two levels + and − with response (or global performance metric) *Y*, a notional test matrix is organized as shown in Table 33. If the singular effects A,B,C, the two-factor interactions, AB, BC, AC, and the three-factor interaction, ABC, are symbolized collectively by the set of factors or interactions q, where q ={A, B, C, AB, BC, AC, ABC}, then the respective effect of an element of q_i on the response Y can be calculated by using Equation 26.

[164] Douglas C. Montgomery, *Design and Analysis of Experiments, Second Edition* (New York: Wiley, 1984) 11-18, 261-265.

Table 33: Two-level (+, −), Three Factor (A,B,C) Test Matrix with Observed Response Y

		Factors			Response
Standard	**Run**	**A**	**B**	**C**	**$Y_{standard}$**
1	random	−	−	−	Y_1
2	random	+	−	−	Y_2
3	random	−	+	−	Y_3
4	random	+	+	−	Y_4
5	random	−	−	+	Y_5
6	random	+	−	+	Y_6
7	random	−	+	+	Y_7
8	random	+	+	+	Y_8

$$(Effect)_{q_i} = \bar{Y}\Big|_{\text{sgn}(q_i)>0} - \bar{Y}\Big|_{\text{sgn}(q_i)<0}$$

where $\bar{Y}\Big|_{\text{sgn}(q_i)>0}$ is the arithmetic mean of responses Y such that the sign $(q_i) > 0$ and similarly $\bar{Y}\Big|_{\text{sgn}(q_i)<0}$ is the arithmetic mean of responses Y such that the sign $(q_i) < 0$

Equation 26

In Equation 26, the sign of q is defined to be the sign of the product of factor(s) of q. For example, using Table 33, the sign for q defined as the interaction of AB is positive for standards 1 (−×− = +), 4 (+×+ = +), 5 (−×− = +), and 8 (+×+ = +). Likewise, the sign for q defined as the interaction of AB is negative for standards 2 (+×− = −), 3 (−×+ = −), 6 (+×− = −), and 7 (−×+ = −).

The significance of the effect, either for a single attribute or for an interaction between attributes, is that it yields insight to the investigator as to what the average amount of increase or decrease a modification of an attribute has on a performance metric. In simple terms, a large relative effect signifies that the attribute of interest has a meaningful consequence on the response. As will be discussed next, a statistical analysis known as the analysis of variance (ANOVA) is subsequently done in order to quantify the statistical significance (or distinguishable from experimental "noise") of the observed effect, i.e., the level of certainty that the measured effect is not simply due to chance or "noise" in the data.

4.2.4 Analysis of Variance (ANOVA)

After the effects have been catalogued, an ANOVA routine was used to quantify the statistical significance of each observance. To aid in quickly identifying this significance, a method based on the creation of Pareto charts depicting the absolute value of each effect (Effect)q_i—charted from largest to smallest—was used.[165] The Pareto chart provides a quick look at the largest effects and helps to identify the observed effects that are the statistically outlying contributors to the system response. In the Pareto chart, the y-axis is the absolute value of the average change in the response metric over acceptable and enhanced levels of that attribute. This method expediently identifies those effects which are subsequently screened to ensure that each identified effect has an F-test commensurate with some level of confidence, e.g., 90%.

[165] Mark Anderson and Patrick Whitcomb, *DOE Simplified Second Edition* (Florida: CRC Press, 2007), 47-52.

Having identified the significant or distinguishable effects, the first step in the ANOVA process is to calculate the sum of squares for (Effect)q_i (or, for simplicity, just $Effect_i$), SoS_i using Equation 27. In this equation, N is the number of runs, which is 8 for a full factorial, 2^3 DOE. The sum of squares for the model and residual, SoS_{model} and $SoS_{residual}$, respectively, are calculated using Equation 28. In this equation, n is the number of statistically distinguishable effects ($n \leq M$), where M is the total number of effects studied. Note, the degrees of freedom of the residual is M-n. Then, the mean square for the factor (or interaction) q_i, the model, and the residual are MS_i, MS_{model} and $MS_{residual}$ respectively, found using Equation 29. Last, use Equation 30 to calculate the F-value. In this equation, $MS_{residual}$ is the collection of effects not considered to be distinguishable, i.e., forming the residual. Table 34 has an abbreviated list of critical F-values used in this study. In this table, the first column has the number of elements in the numerator (NUM) and in the denominator (DEN). For example, if one was evaluating the statistical significance of a single attribute (NUM = 1) against a residual composed of 5 attributes (DEN = 5), one references the second row (1/5) for the F-value corresponding to either the 90% or 95% confidence level.

For a 2^3 DOE framework, there are 7 degrees of freedom, some fraction of which are statistically distinguishable (observed effects) and the remainder assumed as residuals. In this framework, the 7 degrees of freedom (M = 7) using the capital letter abbreviations for the fighting vehicle principal attributes are S, L, M, SL, SM, LM, and SLM. As an example, if two attributes appeared dominant in magnitude to the group, then the model has two degrees of freedom (n = 2) and the residual has 5 degrees of freedom (M – n = 5). To state the statistical certainty associated with the effect under investigation in the model, the F-value calculated must be greater than the value associated with the cross-referenced value associated with the NUM and DEN intersection as observed in a distribution table.[166] Those treatments or attributes with at least 90% confidence, or an F-value commensurate with 90% certainty, are typically considered significant or distinguishable. Higher levels of certainty can be established based on the risk tolerance of the investigator and the desired objective of the experiment, i.e., exploratory versus confirmatory. As this was an exploratory exercise, 90% was considered adequate to distinguish between significant and less significant effects.

$$SoS_{\mathrm{i}} = \frac{N}{4}\left(Effect_{\mathrm{i}}^{2}\right) \qquad \text{Equation 27}$$

$$SoS_{\mathrm{model}} = \sum_{i=1}^{n} SoS_{i}\ ,\ SoS_{\mathrm{residual}} = \sum_{i=1}^{M-n} SoS_{i} \qquad \text{Equation 28}$$

$$MS_{\mathrm{i}} = \frac{SoS_{\mathrm{i}}}{1}\ ,\ MS_{\mathrm{model}} = \frac{SoS_{\mathrm{model}}}{n}\ ,\ MS_{\mathrm{residual}} = \frac{SoS_{\mathrm{residual}}}{M - n} \qquad \text{Equation 29}$$

$$F_{value,i} = \frac{MS_{\mathrm{i}}}{MS_{\mathrm{residual}}}\ ,\ F_{value,\mathrm{model}} = \frac{MS_{\mathrm{model}}}{MS_{\mathrm{residual}}} \qquad \text{Equation 30}$$

Table 34: Critical F-values for Statistical Significance at the 90% and 95% Confidence Levels [167]

NUM / DEN	90%	95%
1 / 6	3.78	5.99
1 / 5	4.06	6.61
1 / 4	4.55	7.71
2 / 5	3.78	5.79
3 / 4	4.19	6.59

166 Mark Anderson and Patrick Whitcomb, *DOE Simplified Second Edition* (Florida: CRC Press, 2007), 189-194.
167 Source for critical F-values is www.statsoft.com/textbook/distribution-tables.

The Pareto chart can be made more meaningful by nondimensionalizing the effects by dividing the absolute value of the dimensional effect by its associated standard error (which has the same units as the effect) (Equation 31).

$$\text{t-value}_{\text{i}} = \frac{\left|Effect_{\text{i}}\right|}{\sqrt{MS_{\text{residual}}\left(\frac{1}{N_+}+\frac{1}{N_-}\right)}} = \frac{\left|Effect_{\text{i}}\right|}{\sqrt{MS_{\text{residual}}\left(\frac{1}{4}+\frac{1}{4}\right)}} = \frac{\left|Effect_{\text{i}}\right|}{\sqrt{MS_{\text{residual}}\left(\frac{1}{2}\right)}} \qquad \text{Equation 31}$$

In this equation, the subscript *i* is the factor (or interaction) of interest, and MS_{residual} is the mean square of the residual. For a 2-level, 3-factorial experiment, the value for N_+ and N_-, i.e., the number of runs for which sgn $q_i > 0$ and sgn $q_i < 0$, respectively, are both 4, so the denominator of the equation simplifies to the square root of one-half of the mean square of the residual.

This is known as a t-value or t-test. Similar to the F-test, a critical t-value associated with a confidence level, e.g., 90%, can by plotted on the nondimensionalized Pareto chart to highlight those attributes providing statistically distinguishable levels of effect to the performance metric of interest. The critical t-values, also available in tabular form (not shown here), only requires the degrees of freedom of the residual (M-n) for reference. However, using the nondimensionalized Pareto chart the observer may lose contextual reference for the relative contribution to the performance metric or system response of interest.

4.2.5 Example Implementation of DOE and ANOVA: Rancher Truck Options

In order to demonstrate the DOE and ANOVA methodology, we revisit the rancher and his search for a replacement truck one last time. As a quick reminder, the rancher needs a new truck and is trying to decide between two models: Alpha and Beta. Having seen the decision support data, the rancher settled on purchasing the Beta. However, when finalizing the details of the purchase, he was presented with three sets of options: standard or high stiffness sets of leaf springs; two-wheel or four-wheel drive powertrain; and standard or oversized tires. The costs of these options were all comparable, so his main focus was on the performance related to these options, namely the time it takes to load and drive the vehicle on a short, challenging cross-country course representative of a repetitive task at the ranch. In an effort to make the sale, the dealer made arrangements for the rancher to conduct a comparison test using the DOE and ANOVA methodology. The framework is a two-level, three-factorial experiment.

The test (experiment) will be the average course lap time per standard, where a standard is the predetermined set of options in accordance with the DOE test-matrix (Table 35). After a random run order is established (second column), and the experiment is completed, the DOE matrix is fully populated. In this table, there is only one effect of interest (Y), namely, average lap time to complete a repetitive task for which the rancher plans to use the new truck. The term "standard" refers to the unique factorial combination of experimental factors applied for a given run and the term "run" is the randomly generated sequence number for the successive iteration through the set of standards, i.e., the rotation order in which the standards will be run.

Table 35: DOE Matrix for Rancher Truck Options

Standard unique combination of experimental factors	**Run** rotation order	**Springs** standard or stiff [±]	**Powertrain** 2-wheel or 4-wheel drive [±]	**Tires** small or large [±]	**Average time** Y [s]
1	3	−	−	−	31
2	5	+	−	−	24
3	6	−	+	−	29
4	7	+	+	−	22
5	2	−	−	+	32
6	8	+	−	+	26
7	1	−	+	+	31
8	4	+	+	+	25

On average, the effect of the stiffer springs (calculated using Equation 26 as demonstrated below) reduced the course lap time by 6.5 s. The subscript for *Y* refers to the standard number (or cross reference to the factorial combination) applied for that experimental run. Note that the effect of the stiffer springs is essentially the average lap time of trucks with stiffer springs minus the average lap time of trucks with the standard springs.

$$Effect_{\text{spring}} = \frac{Y_2 + Y_4 + Y_6 + Y_8}{4} - \frac{Y_1 + Y_3 + Y_5 + Y_7}{4} = \frac{24 + 22 + 26 + 25}{4} - \frac{31 + 29 + 32 + 31}{4} = -6.5 \text{ s}$$

On the other hand, on average, the effect of the 4-wheeled powertrain was to reduce the lap time by 1.5 s.

$$Effect_{\text{powertrain}} = \frac{Y_3 + Y_4 + Y_7 + Y_8}{4} - \frac{Y_1 + Y_2 + Y_5 + Y_6}{4} = \frac{29 + 22 + 31 + 25}{4} - \frac{31 + 24 + 32 + 26}{4} = -1.5 \text{ s}$$

Finally, the average effect of increased tire size was to increase the lap time by 2 s.

$$Effect_{\text{tire}} = \frac{Y_5 + Y_6 + Y_7 + Y_8}{4} - \frac{Y_1 + Y_2 + Y_3 + Y_4}{4} = \frac{32 + 26 + 31 + 25}{4} - \frac{31 + 24 + 29 + 22}{4} = 2 \text{ s}$$

At this point, it appears that the stiffer shocks have the greatest impact on reducing the time it takes to complete this task on the ranch. The addition of four-wheel drive also helps, but not as much. The larger tires have a detrimental effect, as seen by the positive number which indicates an increase in time.

Similarly, the average interactions of shocks and powertrain, shocks and tires, powertrain and tires, and finally any three-way interaction between all of the factors are calculated. Interestingly, there was no synergism between the stiffer springs and the 4-wheeled power train.

$$Effect_{\text{spring}\times\text{powertrain}} = \frac{Y_1 + Y_4 + Y_5 + Y_8}{4} - \frac{Y_2 + Y_3 + Y_6 + Y_7}{4} = \frac{31 + 22 + 32 + 25}{4} - \frac{24 + 29 + 26 + 31}{4} = 0.0 \text{ s}$$

Meanwhile, there were only modest levels of interaction between springs and tire size, as well as powertrain option and tire size.

$$Effect_{\text{spring}\times\text{tire}} = \frac{Y_1 + Y_3 + Y_6 + Y_8}{4} - \frac{Y_2 + Y_4 + Y_5 + Y_7}{4} = \frac{31 + 29 + 26 + 25}{4} - \frac{24 + 22 + 32 + 31}{4} = 0.5 \text{ s}$$

$$Effect_{\text{powertrain}\times\text{tire}} = \frac{Y_1 + Y_2 + Y_7 + Y_8}{4} - \frac{Y_3 + Y_4 + Y_5 + Y_6}{4} = \frac{31 + 24 + 31 + 25}{4} - \frac{29 + 22 + 32 + 26}{4} = 0.5 \text{ s}$$

Based on the small values generated for all three calculations, it appears there is very little interaction between the three attributes. For thoroughness, the final calculation considers the possibility of a three-way interaction between all of the options. As anticipated, there is no distinguishable effect.

$$Effect_{\text{spring}\times\text{powertrain}\times\text{tire}} = \frac{Y_2 + Y_3 + Y_5 + Y_8}{4} - \frac{Y_1 + Y_4 + Y_6 + Y_7}{4} = \frac{24 + 29 + 32 + 25}{4} - \frac{31 + 22 + 26 + 31}{4} = 0.0 \text{ s}$$

At this juncture, it appears the stiffer set of springs yields the best increase in performance (as measured by a reduction in lap time). To establish a statistical basis for confidence in this observation, an ANOVA is performed on the data. The effects of single attributes, double interactions, and three-way interaction are ranked and plotted on a Pareto chart (Figure 40). In the chart, *S*, *T*, and *P* represent the effect due to the springs, the tires, and the powertrain, respectively. Any combination of *S*, *T*, *P* indicates an effect due to some interaction between the attributes. Additionally, a parenthetical notation indicates the effect is negative. In this specific example, that means a reduction in time for the task of interest. It is clear from this chart that the effect of the springs, tires, and powertrain dominate the collective group of single attribute effects, as well as their two-way and three-way interactions. Enhanced springs and tires reduce the task time, while an enhanced powertrain increases it.

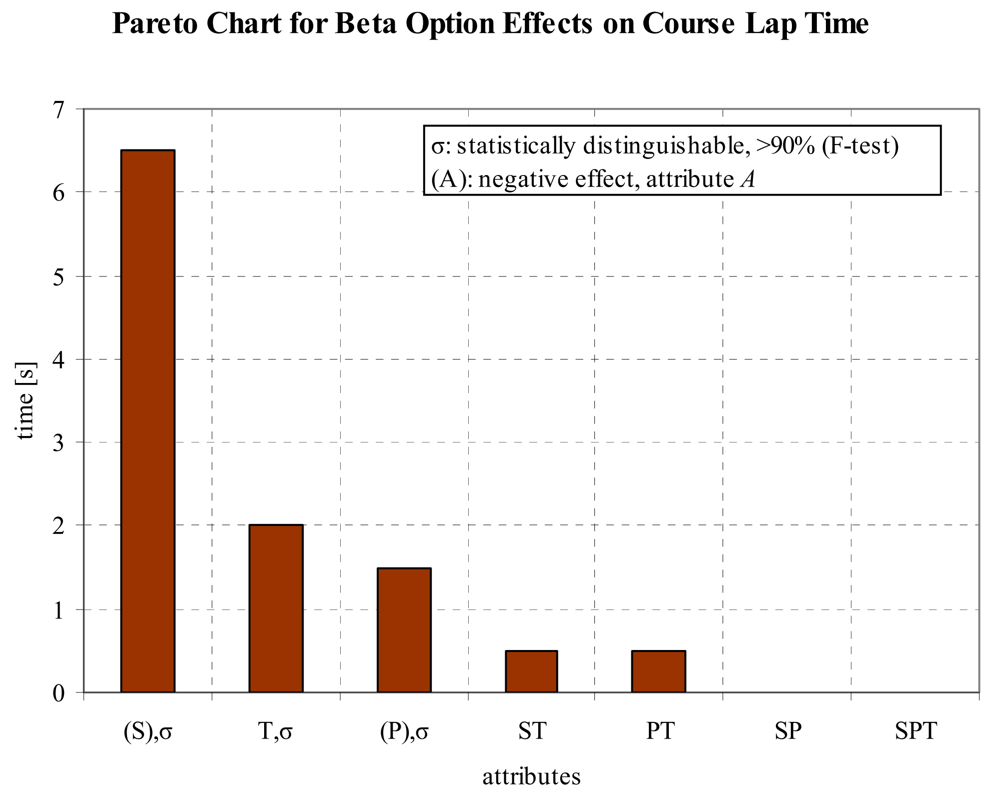


Figure 40: Pareto chart for time effects on the Beta options for the rancher problem. This chart includes the results from the two-level, three-factorial experiment for the Beta truck and the three option choices (S = springs, T = tires, P = powertrain). Negative effects are labeled parenthetically, and statistically distinguishable effects are followed by a σ.

The next step is an F-test to determine the statistical significance of the effects using an ANOVA routine. The Beta truck option example has 7 degrees of freedom (DoF): S, T, P, ST, PT, SP, SPT. Table 36 has the values and procedures used in an ANOVA routine in order to generate the F-values so that the statistically distinguishable effects can be identified.

In this table, Equation 27 is used to calculate the SoS for each attribute, and Equation 28 is used to calculate the SoS for the model and residual, respectively. In this example, the model is assumed to have 3 DoF and the residual have 4 DoF. (Differentiating the statistically distinguishable effects from the remainder can be an iterative process.) Equation 29 is used to calculate the mean sum of squares (MS) for each effect, the model, and the residual. Finally, Equation 30 is used to calculate the F-value for each effect and the model.

Table 36: ANOVA for Beta Truck Options.

	SoS[168]	DoF	MS	F-value
model	$2(-6.5)^2 + 2(-2)^2 + 2(1.5)^2 = 97$	3	97/3 = 32.33	32.33/0.25 = 129
springs	$2(-6.5)^2 = 84.5$	1	84.5/1 = 84.5	84.5/0.25 = 338
tires	$2(-2)^2 = 8$	1	8/1 = 8	8/0.25 = 32
powertrain	$2(1.5)^2 = 4.5$	1	4.5/1 = 4.5	4.5/0.25 = 18
residual	$2\,(0.5)^2 + 2(0.5)^2 + 2(0)^2 + 2(0)^2 = 1.0$	4	1/4 = 0.25	

The F-values are subsequently cross-referenced with a cumulative distribution table (abbreviated Table 34) at a desired confidence level. In doing so, since the generated F-values are greater than the critical values found in the 90% table, we can say with >90% certainty that the stiffer springs were the greatest source of improved performance for the truck, followed by the larger tires. The powertrain had a negative effect on performance and should be left at the low level. For one degree of freedom (numerator) and four degrees of freedom (denominator), at 90% certainty the F-value is

[168] For N = 8, N/4 = 2, therefore each squared effect in this column is multiplied by 2.

4.55, and at 95% certainty the F-value is 7.71. The same procedure can be applied for other performance metrics of interest, with each metric considered having a unique set of effect values for the model and residual.

As previously discussed, the Pareto chart can also be nondimensionalized on a t-value scale (Equation 31), and a critical t-value for 90% certainty can be plotted across the attribute t-values to visually highlight the statistically distinguishable attributes (Figure 41). In this figure, each dimensional effect has been transformed to a nondimensional t-value. For this example, with the residual having 4 degrees of freedom (DoF), the critical t-value is 2.132 (green horizontal dashed line across Figure 41). Thus, in this illustration, the effects of S, T, and P are statistically distinguishable for the truck performance. Based purely on this one performance metric (course lap time), stiffer springs appear to be the best single upgrade for the rancher's new truck purchase.

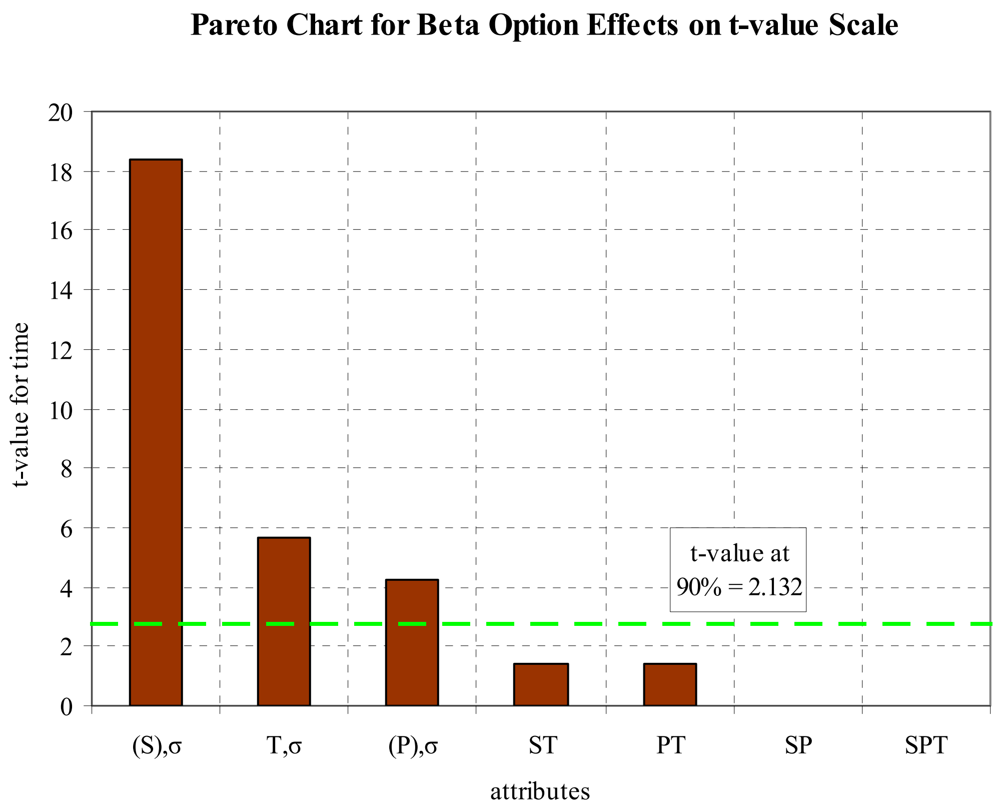


Figure 41: Pareto chart for Beta option effects on t-value for the rancher problem. Once again, the magnitude of effect for the three option choices (S = springs, T = tires, P = powertrain) are plotted, this time on a nondimensional t-value scale. The critical t-value for a residual having 4 degrees of freedom (green dashed line) is plotted, and any effect bar extending above this threshold can be considered distinguishable with 90% confidence.

In summary, the steps necessary to use the data from a two-level, full-factorial, DOE experiment and conduct ANOVA are:[169]

1. Calculate effects of factors and interactions on system response(s) of interest.
2. Sort absolute value of effects in descending order.
3. Plot absolute value of effects on a Pareto chart.
4. Label distinguishable effects (presumed model).
5. Label indistinguishable effects (presumed residual).
6. Calculate each effect's sum of squares (SoS).
7. Construct ANOVA table, calculate mean squares (MS) and F-values.
8. Using tables, identify critical F-values for DoF at a 90% confidence level.
9. Iterate, if necessary (returning to step 4).
10. Plot main effect(s) and interaction(s). Interpret results.
11. If desired, plot the nondimensional t-value Pareto chart with critical t-value.

4.2.6 Principles of DOE to Investigate Principal Attribute Effects and Interactions

There are three basic principles to observe when conducting the DOE method, in this case to investigate the survivability, lethality, and mobility attribute effects and interactions. First, conduct the basic experiment in repetition. In this specific case, the experiment was a search and destroy mission performed repetitively by trained ROTC cadet operators fighting with a prototypic combat vehicle of varying design specification with respect to a 2^3 DOE construct.

[169] Mark Anderson and Patrick Whitcomb, *DOE Simplified Second Edition* (Florida: CRC Press, 2007), 61-62. This list has been modified from the 12-steps presented in the text. Anderson and Whitcomb also include steps for plotting effects using a half-normal y-axis scale.

The next principle to observe is randomization. As will be discussed in the conduct of the experiment, the ROTC cadet operators were randomly assigned combat platforms for each mission set. Furthermore, candidate vehicle assignment was also randomized across the operator population during the entire experiment.

The last principle referred to in the DOE construct is blocking. Also to be expounded upon in the description of the methodology, the session was broken down into two distinct blocks: tracked vehicle trials and wheeled vehicle trials. In both blocks, the same group of trained operators was used after all were trained to a baseline standard of proficiency. Training was done prior to entering the blocked phase of the experiment.

4.2.7 Interactions Among Principal Attributes

For a properly designed experiment, there should be observable responses with respect to variations in attributes. Responses may also be attributed to interactions between attributes. To aid in classifying the types of observable interactions, these effects can be categorized as resembling one of four types with various subtypes.

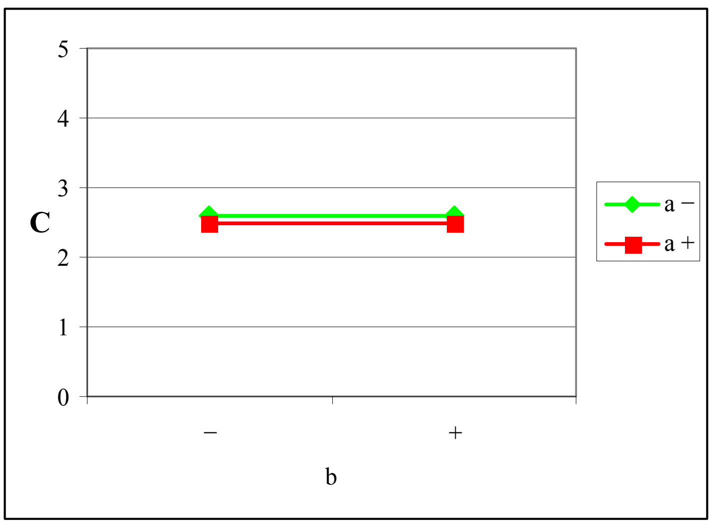
In the following figures, a notional response C is presented as a function of two attributes a and b at low and high levels indicated as subscripts. The marginals and slope difference are calculated using Equation 32 and Equation 34. The marginal described by Equation 32 and Equation 33 refer to the average difference between the net effect of a and b respectively at high and low thresholds. A low value for an attribute marginal signifies low effect. The absolute value of the slope described by Equation 34 denotes the relative change in the plotted effect at low and high thresholds. A low value for the absolute value of this slope term indicates a low amount of interaction between attributes. A discussion of the observed mathematical relationships for the marginals and slopes is provided in the column adjoining each figure.

$$\text{marginal}_a = \frac{C_{a+b+} + C_{a+b-}}{2} - \frac{C_{a-b+} + C_{a-b-}}{2} \qquad \text{Equation 32}$$

$$\text{marginal}_b = \frac{C_{b+a+} + C_{b+a-}}{2} - \frac{C_{b-a+} + C_{b-a-}}{2} \qquad \text{Equation 33}$$

$$\left|\text{slope}_{a+:a-}\right| = \left|\left(C_{a+b+} - C_{a+b-}\right) - \left(C_{a-b+} - C_{a-b-}\right)\right| \qquad \text{Equation 34}$$

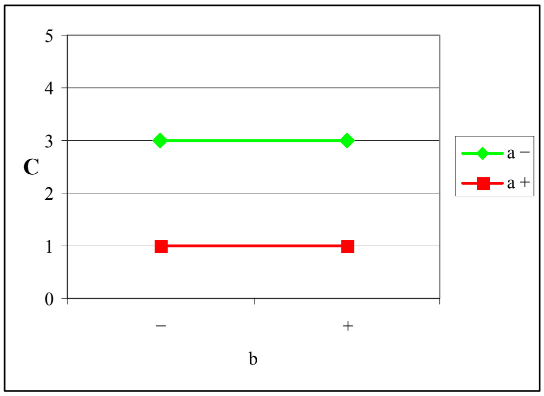
Type I interaction depicted in Figure 42, occurs when neither factor is distinguishable. In other words, the response is stable and insensitive to variations in factors.



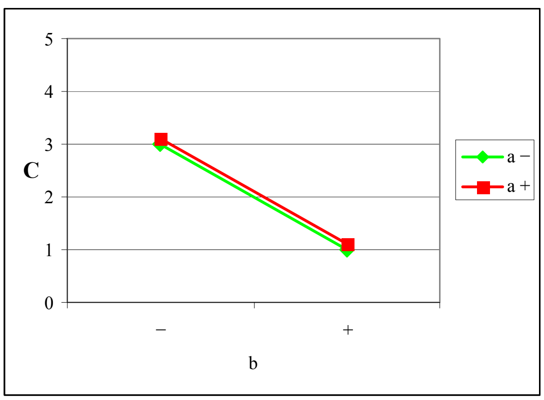
I: In a type I interaction, neither the factors nor the interaction have an effect on the response. Both marginals equal zero, and the slope difference is zero.

Figure 42: Type I attribute interaction and effect.

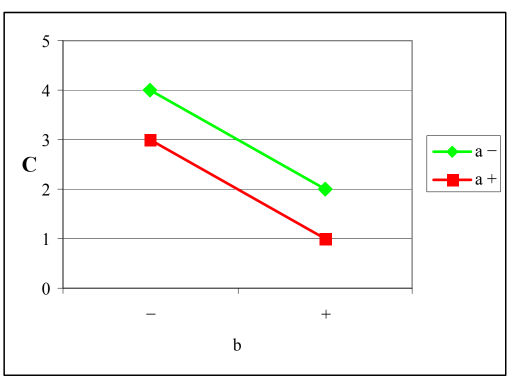
Type II, depicted in three variants in Figure 43, occurs when the factors are distinguishable, but there is no interaction between them. In example IIa, factor *a* is distinguishable, but *b* is not. In example IIb, factor *b* is distinguishable, however *a* is not. In example IIc, both *a* and *b* are distinguishable, although there is no apparent interaction between the factors.



IIa: In a type IIa interaction, factor a has an effect and there is no interaction, ab. The marginal a has some value, the marginal b does not, and the slope difference is zero.



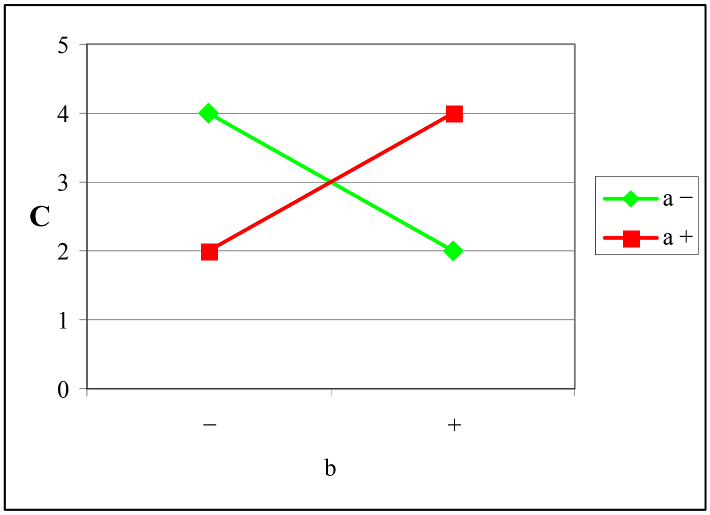
IIb: In a type IIa interaction, factor b has an effect and there is no interaction, ab. The marginal b has some value, the marginal a does not, and the slope difference is zero.



IIc: In a type IIa interaction, factor a and b have an effect and there is no interaction, ab. The marginals for a and b have some value and the slope difference is zero.

Figure 43: Type II attribute interactions and effects.

When a Type III effect occurs (Figure 44), the interaction between factors is distinguishable, but the individual factors are not. This is evident in the cross-pattern of the interaction plots.

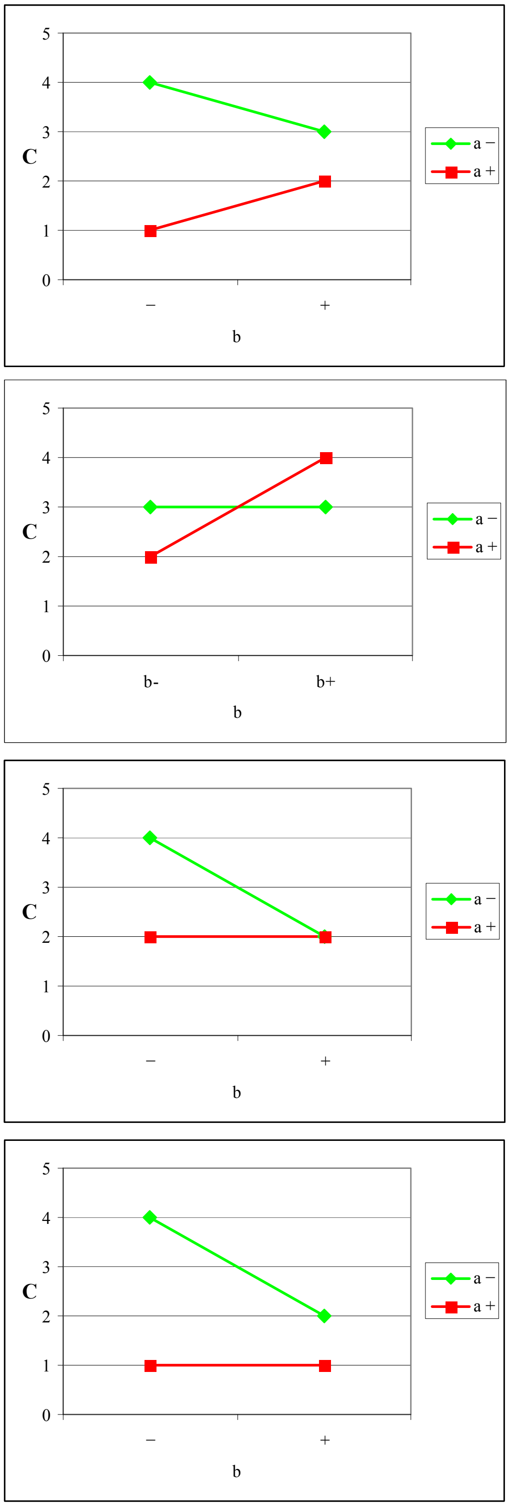


III: In a type III interaction, factor a and b have no effect but there is an interaction ab. The marginals for a and b are zero, and the slope difference has some value.

Figure 44: Type III attribute interaction and effect.

And finally are the Type IV effects where both the factors and the interactions are distinguishable (Figure 45). In example IVa, the interaction, as well as factor *a,* are distinguishable. In example IVb, the interaction, in addition to factor *b*, is distinguishable. In examples IVc and IVd, the interaction and both factors are distinguishable. The subtle difference between IVc and IVd is that the magnitude of the interaction is commensurate with the individual effects in IVd. These graphical examples are the simplest cases, and in practice the observed responses are rarely this clear. Any change in slope between lines indicates an interaction of sorts; the magnitude of this change correlates with the scale of the interaction. These simple examples can still serve as a starting point to categorize the observed interactions and factor effects.[170]

[170] Mark Plonsky, of the University of Wisconsin, presents these examples for a demonstration of two-way DOE and ANOVA. The type classing of the interactions (I-IV) were added as a way of organizing the eight examples he originally constructed. A descriptive example of DOE and ANOVA is presented at his website: www.uwsp.edu/psych/stat/13/anova-2w.htm



IVa: In a type IVa interaction, factor a has an effect and there is an interaction, ab. The marginal for a has some value, the marginal for b is zero, and the slope difference is some value.

IVb: In a type IVb interaction, factor b has an effect and there is an interaction, ab. The marginal for b has some value, the marginal for a is zero, and the slope difference is some value.

IVc. In a type IVc interaction, factor a and b have an effect and there is an interaction, ab is greater in magnitude than the single effects. The marginal for a and b have some value, and the slope difference is some value.

IVd. In a type IVd interaction, factor a and b have an effect and there is an interaction, ab. The marginal for a and b have some value, and the slope difference is some value.

Figure 45: Type IV attribute interactions and effects.

4.3 Methodology

In accordance with the principles of DOE, a set of prototypic vehicles was conceived in order to fully populate a 2^3 test matrix, i.e., acceptable and enhanced levels of survivability, lethality, and mobility. These vehicles were fought by a team of recruited and trained operators within the Joint Reconnaissance and Autonomous Targeting Simulation (JRATS) environment. A collection of workstations for the group of operators served to increase the number of missions run on each platform in an efficient manner. Prior to the conduct of the missions, data from the design report for each variant was collected to produce a set of *a priori* performance metrics, namely mass, cost, volume and schedule index. Mission results were subsequently used to produce a set of *a posteriori* performance metrics, namely win %, blue %, red %, and time %. Each operator fought an assigned, but random variety of tracked and wheeled prototypic platforms within the JRATS simulation environment. Using the previously illustrated DOE/ANOVA techniques, the collected data were interrogated for distinguishable effects due to single attributes or the interactions between them.

4.3.1 Joint Reconnaissance and Autonomous Targeting System (JRATS) Simulation Environment

In order to explore the selective contributions and interactions between the principal attributes of survivability, lethality, and mobility, it was decided that simulations using configurable combat platforms were needed. To build and test a prototypic combat platform with a focus on exploring these principal attributes, a search was conducted to find a software package that could provide these basic simulation requirements. With the resources and within the timeframe available, and after conferring with several program managers at the Program Executive Office for Simulation, Training, and Instrumentation (PEO STRI), a software package used for a Defense Acquisition University (DAU) program manager capstone exercise was recommended as a good candidate. By "good", it is meant that it was available for use, had a relatively short learning curve, and was well developed, having been based on the successful civilian gaming title, *Mindrover*®. The software version developed for the government, known as the *Joint Reconnaissance and Autonomous Targeting System* (JRATS), is a military version of the commercially produced *Mindrover*® robotic fighting vehicle simulation game.[171] *Mindrover*®, originally designed as a space-vehicle robot simulator, was created to provide a user with an environment to build and subsequently battle against opponent space vehicles in virtual reality.[172] The JRATS version sustained the physics-based vehicle dynamics and weapon capabilities, but moved the setting to an urban environment representing a COE combat zone. The JRATS title also produces design reports focused on vehicle performance attributes, as well as relevant program management considerations like cost and schedule implications.[173]

The JRATS environment allows the user to construct a prototypic combat vehicle and then subsequently fight it against a JRATS-generated, autonomous enemy vehicle. This environment dovetails into a capstone exercise where teams design, procure, and virtually fight candidate vehicles for the notional Joint Unmanned Ground-combat Vehicle (JUG-V) program. In JRATS, there are five missions from which to choose, several types of base vehicle chassis upon which to build, and a host of design choices to make in the virtual creation of the fighting vehicle (Table 37). Construction of the prototype was fairly simple; it was similar to using software like *Simulink*® or *LabView*®

[171] Lindsey Thornhill, et. al., "Design of an Agile Unmanned Combat Vehicle – A Product of the DARPA UGCV Program" *Proceedings of SPIE*, Vol. 5083 (September 2003) 358-370.
[172] *Mindrover®: Student Instructions for System Engineer and Test Manager,* Version 2.1gh
[173] Several other titles were investigated including Tacops 4.04 and BCTP. None offered the versatility to prototypically design platform variants as well as JRATS.

in which components are simply dragged and dropped onto a design board, then wired together using a series of connections, functions, and math operators.

Table 37: JRATS Vehicle Design Choices

Category	Choices
Mission	Seek and destroy (passive enemy) Interoperability (passive enemy) Mine detection (passive enemy) Seek and destroy (active enemy) Interoperability (active enemy)
Vehicle Configuration	Tracked Wheeled Hover
Powerplant	Large (high output) Medium (moderate output) Small (low output)
Armor material	Depleted Uranium (DU) Rolled Homogenous Armor (RHA) Steel Superficial
Frame material	Aluminum Titanium Composite
Hull / body material	Aluminum Steel Composite
Movement components	Throttle settings Tread controls (tracked) Steering controls (wheeled) Thruster controls (hover)
Power components	Fuel cell (small or large) Battery (small or large) Auxiliary power unit (APU)
Weapon components	Heavy machine gun Missile (laser guided, single or triple) Missile (unguided, single or triple) Trigger designations[174]
Sensor components	Minesweeper
Miscellaneous components	Laser range finder (LRF) Communications

[174] The course manager for the DAU PMT352 recommended using the Logitech ATK3 user interface with JRATS since the 11 available trigger switches and fine adjustment tuning parameters could be used to dial each prototype to the specificity required.

After deploying and subsequently fighting the vehicle in the combat simulation, JRATS produces a short summary mission completion report, providing the user with a rating of success or failure, elapsed mission time ($time_{mission}$), the friendly vehicle's remaining health ($blue_{mission}$ %), and threat vehicle's remaining health ($red_{mission}$ %). Figure 46 depicts the organization of both design and mission report metrics generated from JRATS. Figure 47 expands the principal attributes from design report metrics and those produced from the after-action report (AAR) provided at the completion of a JRATS mission.

For the purposes of this research, only tracked and wheeled platforms fighting against an active enemy in the urban environment were considered. This mission profile best represented the COE, i.e., a determined enemy fighting from within the confines of a city traversing improved roads.[175] It is well understood that the exclusive scenario chosen represents a small fraction of the range of types of combat one may encounter in full spectrum operations (Figure 48). Additionally, in the form furnished by DAU, JRATS does not allow for interaction between friendly units.[176] In other words, this was a one-on-one combat simulation against a computer opponent in what constitutes a narrow band of the entire array of full spectrum operations. Fortunately, JRATS still afforded the user with a host of vehicle design options including armor materials, weapon packages, and power alternatives.

[175] Jason Conroy and Ron Martz, *Heavy Metal: A Tank Company's Battle to Baghdad* (Virginia: Potomac Books, 2006).

[176] The original *Mindrover* title allowed vehicles to be hosted in a virtual combat arena where one can fight other users and their designs. The military version had this capability at DAU, but they were not able to export the function remotely for use in this research. Attempts were made to import the military vehicles into the original *Mindrover* environment, but compatibility issues prevented this from working properly.

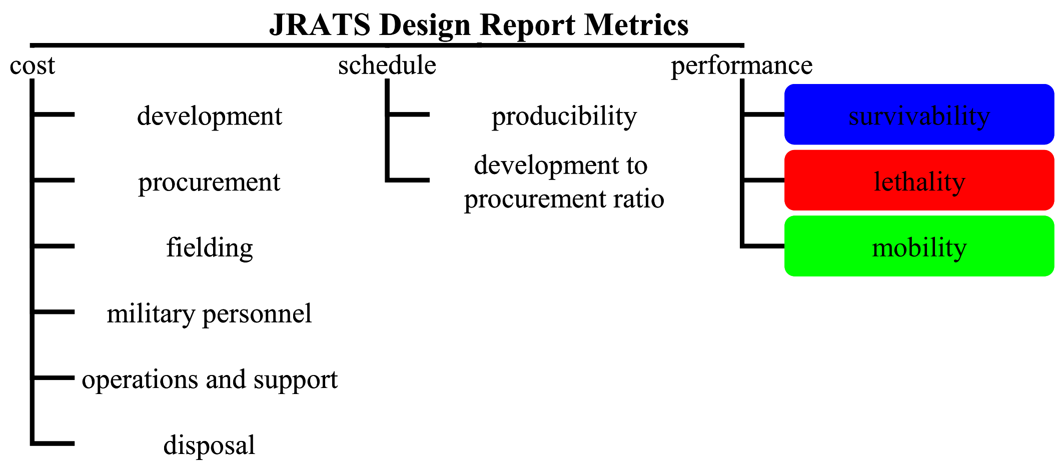


Figure 46: JRATS design report metrics produced for each variant. Metrics classified under the principal attributes are listed in the subsequent figure.

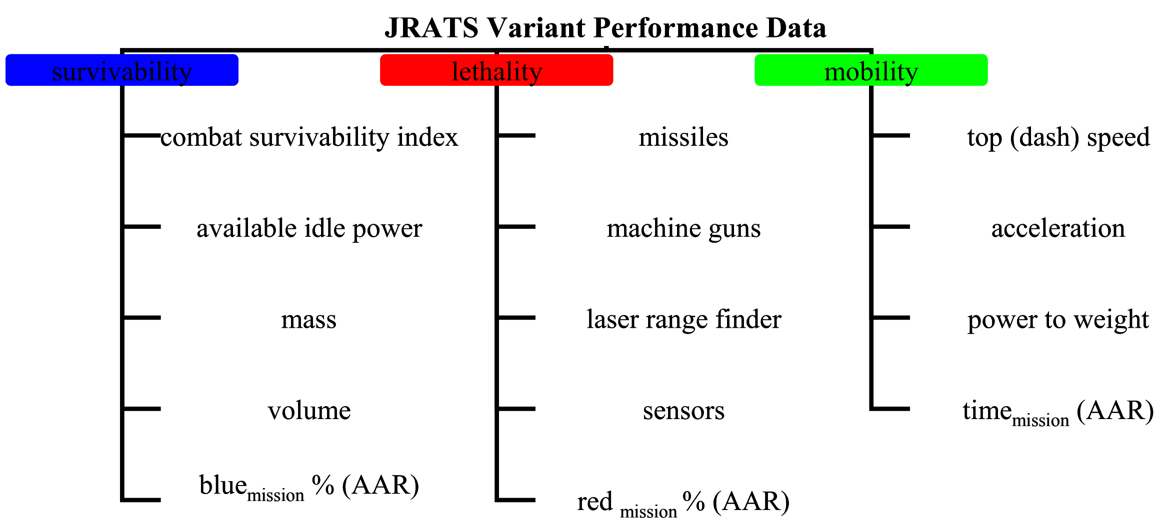


Figure 47: JRATS variant performance data available from both the variant design report and mission after-action report (AAR). Those values produced from the latter are parenthetically labeled “AAR”.

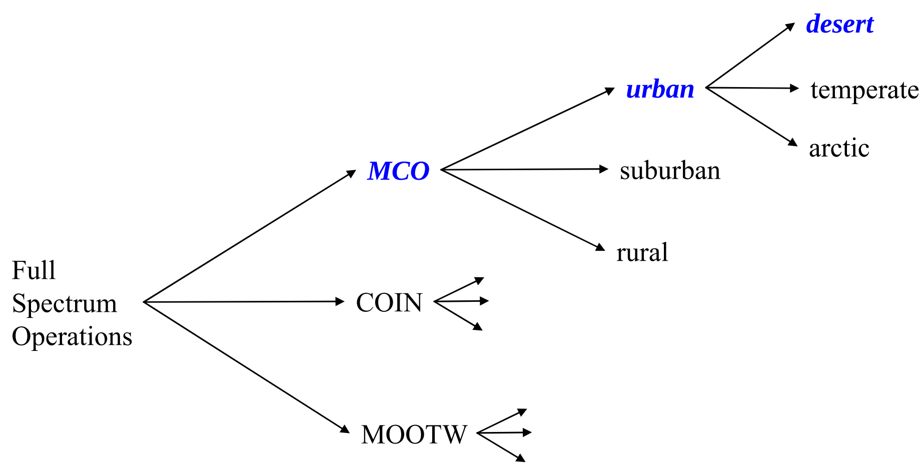


Figure 48: Partial expansion of full spectrum operations into combat variants, population density areas, and climate types, showing those examined in this study. The bold and blue-italicized branch represents the path chosen in JRATS. More specifically, the mission profile is a one-on-one, offensive, search and destroy operation.

4.3.2 Vehicle Design Specifications for DOE

In order to explore the effects and interactions of the three principal attributes, a collection of 18 candidate fighting vehicles was designed. Eight were required for each 2^3 full-factorial, wheeled and tracked experimental DOE matrix. Two additional vehicles, one wheeled and one tracked, were also constructed to serve as training platforms for the mission operators. In building the variants, Anderson's guidance concerning aggressive, but realistic level-setting was considered. He states that "one of the most difficult decisions for DOE, aside from which factors to chose, is what levels to set them. A general rule is to set levels as far apart as possible so one is more likely see an effect, but not exceed the operating boundaries."[177] Anderson later goes on to discuss the value of a controlled, pretrial of factors, or a proof-of-concept experiment for the experiment itself.

[177] Mark Anderson and Patrick Whitcomb, *DOE Simplified Second Edition* (Florida: CRC Press, 2007), 44-45.

To explore the capabilities and limitations of the JRATS software, the designer (author) ran several hundred missions and iteratively designed dozens of vehicles. As a result, a sense of how the attributes should be tuned up and down on each platform was developed. Additionally, instead of thinking of the factors as plus and minus, it was helpful to consider the works of Bhote, who, rather than use terms like plus and minus, or low and high, respectively, recommends the terminology of marginal and best, or acceptable and best.[178] With consideration for the attributes of interest for a ground combat vehicle, the low (or minus) threshold was an *acceptable* level, and the high (or plus) threshold was an *enhanced* level.

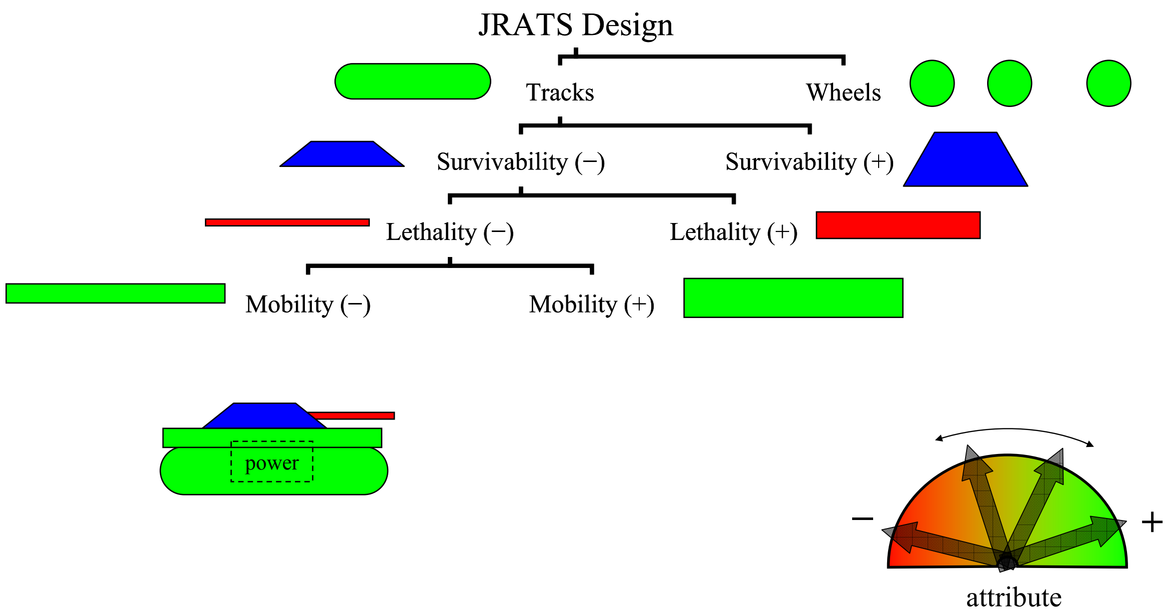


Figure 49: Attribute dial and design tree indicating an acceptable (−) or enhanced (+) setting for design specifications. Note that just the left portion of the tree has been expanded completely, ending in a tracked candidate with an acceptable (−) level of survivability, lethality, and mobility.

[178] Keki Bhote and Adi Bhote, *World Class Quality: Using Design of Experiments to Make It Happen* (New York: AMA, 2000) 241-249.

Considering the tunable performance metrics previously presented in Table 38 and depicted in Figure 49, a design matrix was formulated for the three attributes of survivability, lethality, and mobility at two prescribed levels. The observed performance envelopes from the previous missions completed by the author as preliminary work (approximately 500 missions on a variety of design variants) were reflected upon in constructing the formulations depicted in Table 38. The term *XTV* stands for *experimental tracked* vehicle and *XWV* stands for *experimental wheeled* vehicle; these variants were fought to collect data. Likewise, the numeral succeeding *XTV* or *XWV* is the specific variant in accordance with the matrix. *TTV* and *TWV* are used to designate the *training* tracked and wheeled variants, respectively; these were used for training purposes in order to preserve the integrity of the capabilities in the set of XTVs and XWVs.

Unless otherwise noted, each candidate platform had an identical power package, separate from the power plant, consisting of two fuel cells, two auxiliary power units, and two standard batteries (Table 39 and Table 40).[179] In order to keep a balanced comparison, these elements were subsequently added to the mass and cost values for the platforms. The power elements were connected in parallel to the main virtual busswork in order to share power between the varying locomotive demand and weapon loads. Additionally, tracked vehicles and wheeled vehicles had distinct control mechanisms as prescribed by the JRATS vehicle construction plans. In the tables that follow, a capital letter signifies an enhanced level for an attribute, while a lowercase letter signifies an acceptable level for an attribute. Finally, in the tabular depictions of the factorial designs,

[179] XTV7 had one APU and no batteries. Additionally, XWV3 and 5 had no batteries, and XWV7 had no APUs. The mass and cost of these individual items were later added to maintain an equitable design among candidates.

the relative size of the vehicle turret, cannon, or hull on the accompanying thumbnails is indicative of the level of survivability, lethality or mobility for that variant.

Table 38: Two-level Construction Matrix for Survivability, Lethality, and Mobility

s Acceptable Survivability	**S** Enhanced Survivability
rolled homogeneous (steel) armor aluminum body	depleted uranium armor steel body

l Acceptable Lethality	**L** Enhanced Lethality
2× heavy machine gun laser range finder communications suite ground penetrating radar	2× guided missile pods 2× heavy machine gun laser range finder communications suite ground penetrating radar

m Acceptable Mobility	**M** Enhanced Mobility
low output powerplant aluminum frame	high output powerplant composite frame

Table 39: Experimental Tracked Vehicle (XTV) Variants for DOE with Indicated Levels of Survivability, Lethality, and Mobility

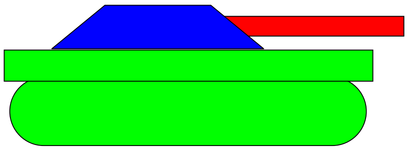
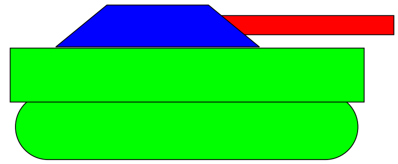
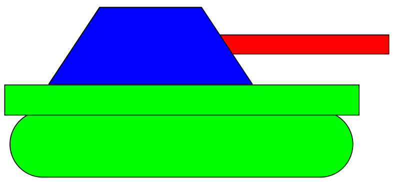
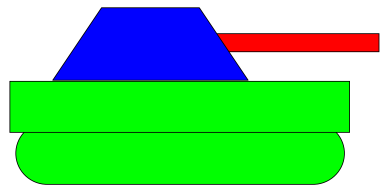
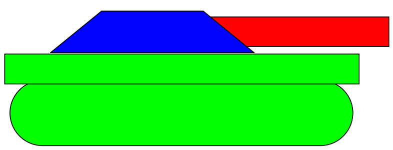
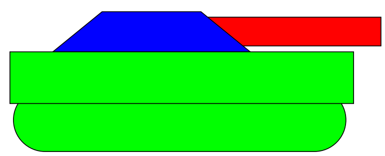
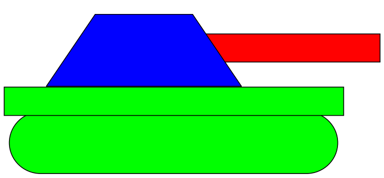
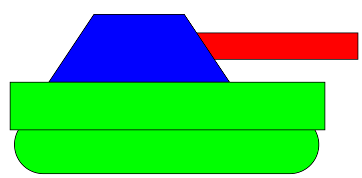
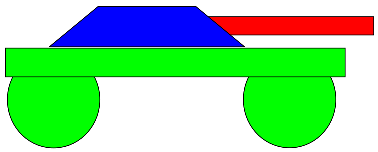
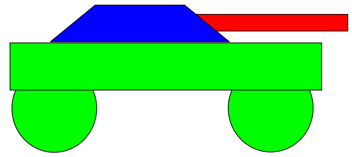
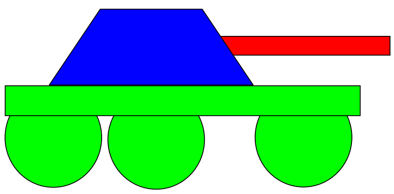
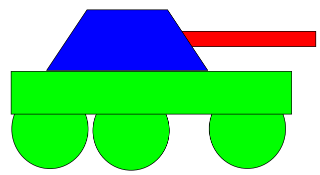
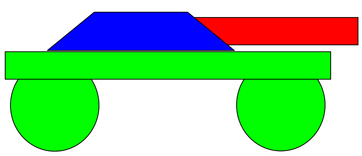
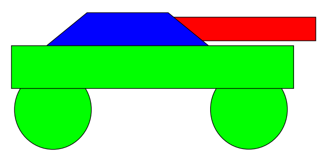
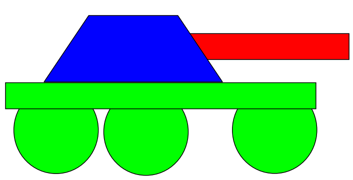
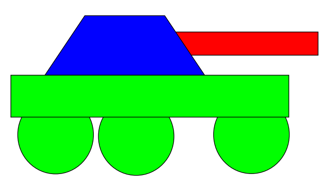
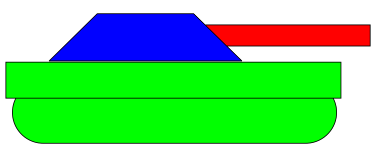
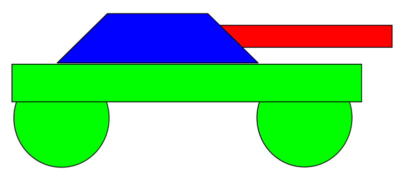
 **XTV1** **slm**	 **XTV5** **slM**
 **XTV2** **Slm**	 **XTV6** **SlM**
 **XTV3** **sLm**	 **XTV7** **sLM**
 **XTV4** **SLm**	 **XTV8** **SLM**

Table 40: Experimental Wheeled Vehicle (XWV) Variants for DOE with Indicated Levels of Survivability, Lethality, and Mobility

 **XWV1** **slm**	 **XWV5** **slM**
 **XWV2** **Slm**	 **XWV6** **SlM**
 **XWV3** **sLm**	 **XWV7** **sLM**
 **XWV4** **SLm**	 **XWV8** **SLM**

As mentioned, the group of ROTC cadet operators were first run through training missions using the TTV and TWV in order to establish a baseline level of proficiency with the JRATS software and user interface. Therefore, in addition to the eight wheeled and eight tracked vehicles for the three-attribute, two-level, full-factorial DOE experiment, a training wheeled vehicle (TWV) and training tracked vehicle (TTV) were also constructed to allow the operators to conduct preparatory missions on impartial platforms representative of those types that would be fought during the record missions using the XTVs and XWVs (Table 41). In this table, the over bar signifies an intermediate level of each attribute, i.e., between acceptable and enhanced. These two vehicles were designed with an intermediate level of survivability, lethality, and mobility (aluminum construction, single missile launcher, medium output powerplant) with respect to an acceptable and enhanced level possessed in the XTVs and XWVs.

Table 41: Training Vehicle Variants, Tracked and Wheeled (TTV and TWV) with Indicated Levels of Survivability, Lethality, and Mobility

 **TTV** $\overline{\textbf{slm}}$	 **TWV** $\overline{\textbf{slm}}$

For reference, a visual depiction of the JRATS design screen is provided as Figure 50. Naming convention within the JRATS vehicle library followed the convention listed in the previous tables. Figure 51 contains a simulation rendering of a completed tracked vehicle design for use in the simulation.

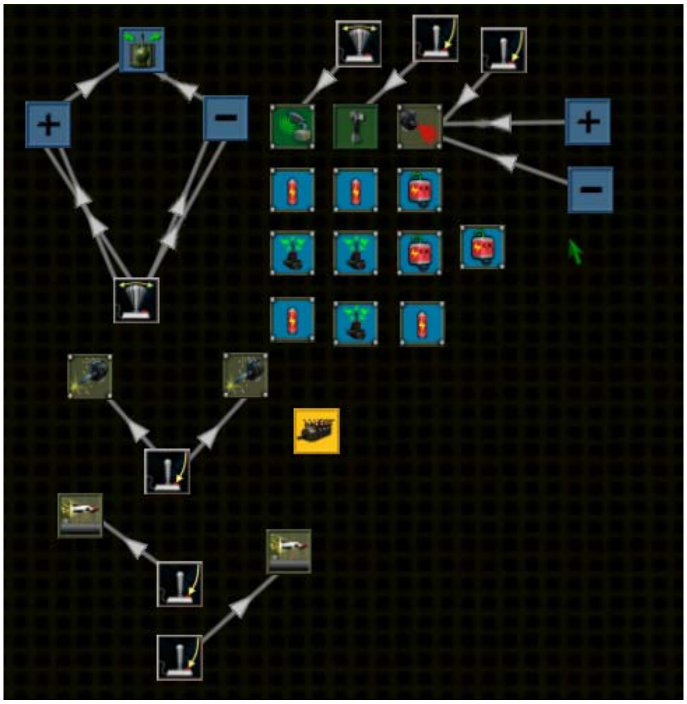


Figure 50: JRATS design screen. Build components are placed on a virtual breadboard. Logic components and interface modules are wired together to form the functional combat platform prototype.

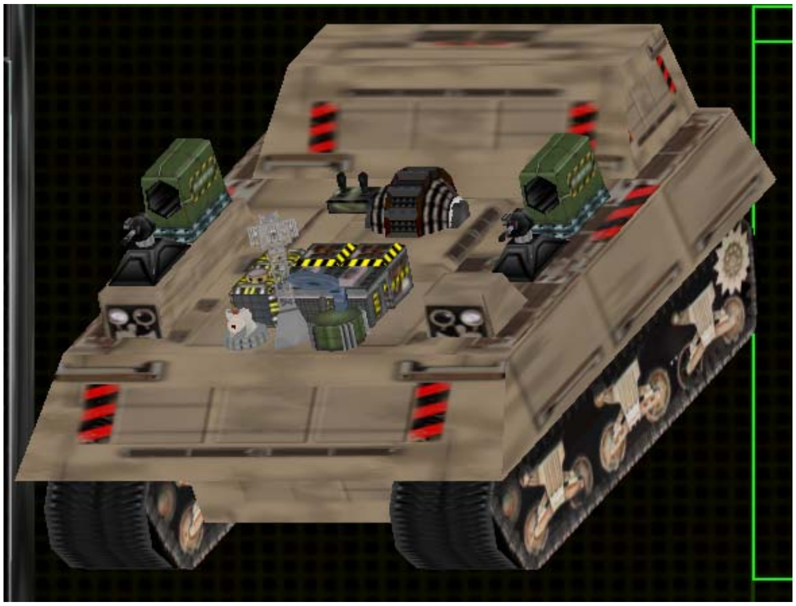


Figure 51: JRATS vehicle rendering of a completed tracked combat platform.

4.3.3 Test Matrix

In accordance with the principle of randomization, a spreadsheet was constructed using a random number generator in conjunction with rules intended to ensure each operator at each workstation did not fight redundant platforms. This was also done to plan an equitable number of missions (120 per variant, or 8 operators fighting 15 missions per variant) for each vehicle.[180]

Experimental Tracked Vehicle Test Matrix (XTVs 1–8)

workstation	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
0-20 min	3	5	2	8	4	5	6	1	2	6	1	4	8	5	3	7
20–40 min	5	6	8	1	3	2	4	7	6	1	5	7	4	2	8	3
40-60 min	6	2	5	3	7	8	1	4	4	8	3	6	2	7	5	1
60-80 min	8	1	3	5	6	4	7	2	8	3	7	1	6	4	2	5

Experimental Wheeled Vehicle Test Matrix (XWVs 1–8)

workstation	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
0-20 min	8	1	5	7	4	2	6	3	5	2	3	1	4	7	6	8
20–40 min	6	4	2	5	3	8	1	7	3	1	8	7	2	4	5	6
40-60 min	4	5	1	3	7	6	2	8	1	6	7	5	8	3	2	4
60-80 min	1	7	6	8	5	3	4	2	6	3	4	2	5	8	7	1

180 Workstations 15 and 16 went unoccupied due to last-minute personal conflicts of the ROTC cadet operators. As willing and able, operators from other workstations assumed extra missions, particularly as time permitted in the XTV block.

4.3.4 Performance Metrics for Analysis

Four *a priori* performance metrics unique to each vehicle and insensitive to the conduct or results of the mission (vehicle mass, per vehicle cost, exterior vehicle volume, and schedule index) were calculated for the design variants. Four *a posteriori* performance metrics as related to the conduct and results of the mission (win %, blue %, red %, and time %) were calculated based on data recorded for each mission run by the 14 operators.

4.3.4.1 *A Priori* Performance Metrics

Vehicle mass for each variant was a simple output value from the JRATS design report. Meanwhile, for cost, from the same variant vehicle design report, five separate costs were summed for each platform: development, procurement, unit, MILPERS (military personnel), O&S (operations and support) and disposal (*Equation 35*). The cost reported represents a major (Acquisition Category or ACAT 1D) program cost for 500 combat systems notionally apportioned among the services, therefore this summed value of associated costs was divided by 500 to produce a per-unit or individual JRATS vehicle cost.[181]

$$\text{cost [\$M]} = (\$_{\text{development}} + \$_{\text{procurement}} + \$_{\text{unit}} + \$_{\text{MILPERS}} + \$_{\text{O\&S}} + \$_{\text{disposal}})/500 \qquad \text{Equation 35}$$

Exterior vehicle volume was estimated from the dimension of the machine gun component, a constant element on each variant. The completed design was rotated in space and subsequently analyzed to approximate the length, width, and height of the

[181] JRATS assumes 20 vehicles for low rate initial production (LRIP) 1, 30 vehicles for LRIP 2, with 50 vehicles destined for the Marine Corps, 150 for the Air Force, and 300 for the Army.

completed platform with respect to this component. Assuming the cannon was 2 m long, an estimate for each platform volume was produced for the set of XTVs and XWVs.

For the schedule index, two dimensionless values were combined from the design report, i.e., the ratio of development to production costs times the producibility index (PI), generated from the variant design report. The ratio of costs produces a value indicative of schedule risk. For example, a system with a low ratio of development to production costs is generally assumed as more mature (less risky) since the majority of funds are being directed toward production. On the other hand, a less mature system with more schedule risk has a larger fraction of funds used to further develop the design, hence a higher value for the fraction of development to production costs. The producibility index is a nondimensional value indicative of the manufacturing challenge associated with the design. The selected performance specifications are provided for the tracked and wheeled vehicles used in the DOE full-factorial matrix, including average values and standard deviation (SD) for the tracked and wheeled candidate blocks (Table 43 and Table 44).

$$\text{schedule index} = \frac{\$_{\text{development}}}{\$_{\text{procurement}}} \times PI \qquad \text{Equation 36}$$

4.3.4.2 *A Posteriori* Performance Metrics

At the completion of each JRATS mission, a short summary report alerted the operator as to whether the mission was a success (win) or not (loss), the residual percentage of health for the operator's (friendly) ($blue_{\mathrm{mission}}$ %) and enemy (red_{mission} %) vehicles, and the expired time for the mission (minutes and seconds). These values were used to calculate four *a posteriori* performance metrics. Win % is simply the fraction of missions won by the platform; it may be considered the most critical global performance metric (Equation 37). Clearly, for win %, more is better. Blue % is the average residual health of the platform for successful missions; it is a proxy of system protection or survivability (Equation 38). In this equation, $blue_{\mathrm{mission}}$ *%* is the residual health fraction for the friendly vehicle for a specific mission, and *time-out* is the occurrence of a mission failure due to an expiration of time, i.e., 15 minutes expired. Here again, for blue %, more is better. Red % is the average residual health fraction for the threat (enemy) platform from the missions; it is a proxy of friendly system firepower or lethality (Equation 39). In this equation, red_{mission} % is the residual health fraction for the threat (enemy) vehicle for a specific mission. For red %, less is better as this means the threat platform had more damage incurred onto it. Time % is the average fraction of time for the mission (Equation 40); it is a proxy of system mobility. In this equation, $time_{\mathrm{mission}}$ is the elapsed time for the mission, or the final time recorded. In this same equation, the 15 minutes in the denominator is the time limit for each mission. For time %, less is better as this means the friendly platform completed the mission faster.

a posteriori **performance metric equation**	**desired direction (▲,▼)**	**Equation #**
$\text{win }\% = \frac{\Sigma(\text{win})}{\Sigma(\text{mission})}$	▲	Equation 37
$\text{blue }\% = \frac{\Sigma(\text{blue}_{\text{mission}}\%)}{\Sigma(\text{win}) + \Sigma(\text{time-out})}$	▲	Equation 38
$\text{red }\% = \frac{\Sigma(\text{red}_{\text{mission}}\ \%)}{\Sigma(\text{mission})}$	▼	Equation 39
$\text{time }\% = \frac{\Sigma(\text{time}_{\text{mission}})}{15\,\text{min}\,\Sigma(\text{mission})}$	▼	Equation 40

4.3.5 8-step Training Model

To build up a statistically representative database of virtual reality mission performance for the tracked and wheeled DOE prototypic combat vehicles, a group of system operators was recruited and trained on the JRATS combat simulation software. The training portion of the experimental session included software and hardware training, tracked vehicle trials, wheeled vehicle trials, and an after-action review. To gain permission for the use of human subjects in this research, an amendment to the existing IRB study was submitted and subsequently approved (Appendix 9–Appendix 12). This amendment documented the purpose of the experiment, as well as the training and collection steps proposed for the session. The 8-step training model was also implemented in order to organize the tasks required to conduct this experiment in an effective manner (Table 42).

Table 42: 8-step Training Model[182]

1. Plan the training
2. Train and certify leaders
3. Recon the site
4. Issue the plan
5. Rehearse the training
6. Execute the training
7. Conduct AAR
8. Retrain as necessary

The training and experiment were planned in conjunction with a University of Texas at Austin ROTC senior lab session.[183] This helped ensure that the subjects were the most militarily experienced cadets available. The proctor (author) served as the primary trainer for the simulation exercises and the cadet chain of command assisted with the experiment protocols. To minimize disruption to cadet schedules, a deployable package of 16 workstations, user interfaces, and training aids was assembled for remote use in the ROTC area. After issuing the plan, a full-factorial test simulation was conducted on every

[182] U.S. Army Field Manual 7-0, *Train the Force.* Headquarters, Department of the Army, Washington, D.C., 2002.

[183] Sharon Begley, "What's Really Human? The trouble with student guinea pigs." *Newsweek,* July 23, 2010. In her article, Begley references the ongoing work of Joseph Henrich of the University of British Columbia. In Henrich's published paper in *Behavioral and Brain Sciences*, he explores a weakness in some human subject experiments in that the analysis does not account for innate differences between the student subject population and the greater population. In this experiment, an effort was made to chose subjects which were representative of the military they will soon serve in.

workstation for each DOE XTV and XWV variant to ensure functionality of all test equipment (hardware and software).

Upon arriving at the training site, a block of instruction was provided on the general topic of fighting vehicles and the concepts of survivability, lethality, and mobility. This included a discussion about platform survivability, lethality, and mobility, as well as a review of actions-on-contact and battle drills. After a brief orientation to the individual workstations, a series of training and familiarization missions was conducted with these UT Austin ROTC volunteer operators.

The formal training session for JRATS consisted of driver training on a wheeled and tracked platform, weapon training against a passive threat vehicle, weapon training against an active threat vehicle, and training missions simulating the same conditions the operator would encounter during the record portion of the experimental session. This training followed the "crawl-walk-run" method. The "crawl" training missions on the wheeled and tracked training vehicles were analogous to initial driver training. No weapons were enabled, and the enemy was kept in a passive mode. None of the cadets had ever driven a tracked vehicle before, therefore this training was vital to develop operator skills to an acceptable level of performance when navigating a tracked platform in an urban environment. The "walk" training missions included single weapon systems enabled against a passive enemy.[184] The first weapon activated for use was the heavy machine gun and laser range finder (LRF), and the second weapon was the guided missile pod with the LRF.

The "run" training missions were full-speed engagements against an active enemy in the same simulated urban environment. These missions also included formal reporting of mission performance to ensure all subjects recorded the data in a satisfactory manner

[184] The passive enemy setting in JRATS keeps the enemy from tracking or firing on the friendly platform.

(win/loss, $blue_{mission}$ %, $red_{mission}$ %, time). The performance review also helped identify those subjects requiring remedial training. Group learning was encouraged during the training session with in-stride discussions of the tactics, techniques, and procedures (TTPs) which appeared conducive with effective missions.

All training missions were conducted on the tracked and wheeled training vehicle variants (TTV and TWV) in an effort to preserve the integrity of the record mission platforms (XTVs and XWVs) designed for the experiment. A copy of an example scorecard is included as Appendix 14. The operational graphic used to orientate the subjects to the virtual reality mission environment is depicted in Figure 52. This was provided to the operators during the training mission in order to provide an overhead view of the terrain to include general axis of movement (clockwise around city) and potential sites for enemy activity (red stars on graphic). A snapshot of the terrain depicted in the JRATS simulation is provided in Figure 53. Operators were instructed to move about the city in a clockwise fashion until the enemy vehicle was spotted. Upon making visual contact with the enemy, the operators were instructed to conduct actions on contact in accordance with the seek and destroy mission, i.e., to return fire and destroy the threat vehicle.

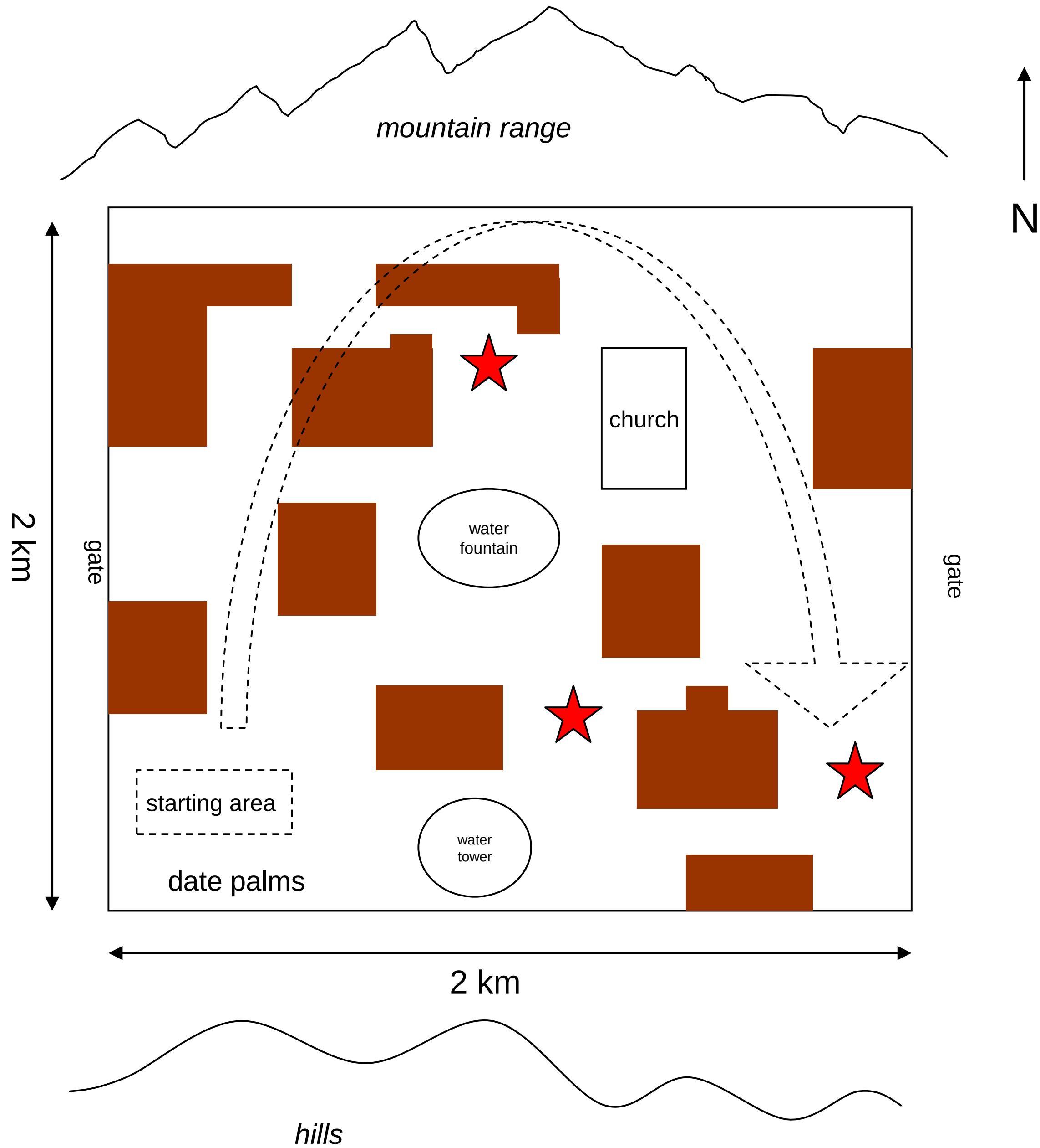


Figure 52: JRATS operational graphics for urban combat mission against an active enemy. The dotted arrow indicates the directed scheme of maneuver for the operators to move through the city. The red stars are the locations in the city where enemy contact is likely, i.e., where the computer randomly spawns the threat platform.

Figure 53: JRATS urban environment screenshot. The simulation does not account for collateral damage to the structures in the city.

4.4 Data Collection

After each mission, the operator recorded a win or loss, the residual health for the friendly vehicle ($blue_{mission}$ %), the residual health for the threat vehicle ($red_{mission}$ %), and mission time that expired. A winning mission would have some value for $blue_{mission}$ %, a zero for red $\%_{mission}$, and some residual mission time. Moreover, a losing mission due to catastrophic insult would have a zero for $blue_{mission}$ %, some value for $red_{mission}$ %, and some residual mission time. A losing mission due to a "draw" or mission time-out would have some values for both $blue_{mission}$ % and $red_{mission}$ % and a zero for residual time. In rare instances, both vehicles destroyed each other simultaneously. This was also recorded as a loss, with both friendly and threat platforms having zero residual health ($blue_{mission}$ % = $red_{mission}$ % = 0%).

Data collected contributed to the formulation of global *a posteriori* performance metrics, the most important one being mission success (win %), and the other three serving as proxies for assessing system survivability (blue %), lethality (red %), and mobility (time %).

Table 43: Summary of XTV Cost, Schedule, and Performance Specifications[185]

	cost [$M]	**schedule index**	**mass [kg]**	**volume [m^3]**	**v_{max} [km/hr]**	**a [m/s^2]**
XTV1	6.44	151	1375	8	15	3
XTV2	7.14	159	1555	16	14	2
XTV3	8.18	200	1415	9	15	3
XTV4	8.56	201	1595	16	13	2
XTV5	7.03	159	1455	6	17	4
XTV6	7.53	159	1635	16	15	3
XTV7	8.44	142	1455	8	17	4
XTV8	8.94	202	1675	16	15	3
XTV_{avg}	7.78	171	1520	12	15	3
SD	0.88	25	109	5	1	1

Table 44: Summary of XWV Cost, Schedule, and Performance Specifications[186]

	cost [$M]	**schedule index**	**mass [kg]**	**volume [m^3]**	**v_{max} [km/hr]**	**a [m/s^2]**
XWV1	6.34	154	775	6	18	6
XWV2	6.84	155	955	11	15	5
XWV3	7.75	156	805	7	18	6
XWV4	8.25	197	955	11	15	5
XWV5	6.72	120	845	5	20	8
XWV6	7.22	156	1035	10	17	7
XWV7	8.14	205	805	6	21	9
XWV8	8.64	199	1075	11	16	7
XWV_{avg}	7.49	168	906	8	18	7
SD	0.83	30	114	3	2	1

[185] Note the vehicle mass indicative of a robotic vehicle. The maximum velocity may also be indicative of the performance of the platform, but the vehicles move quite rapidly through the environment since it appears the JRATS simulation runs at 5× speed. SD is the standard deviation for each column.
[186] Ibid.

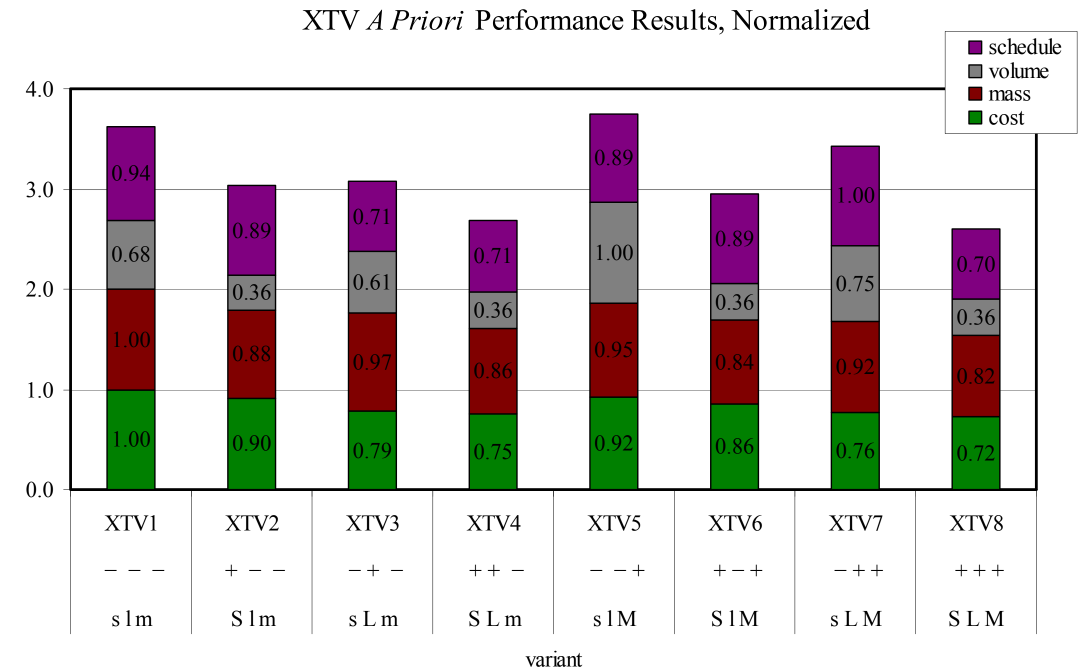


Figure 54: XTV *a priori* performance results, normalized.

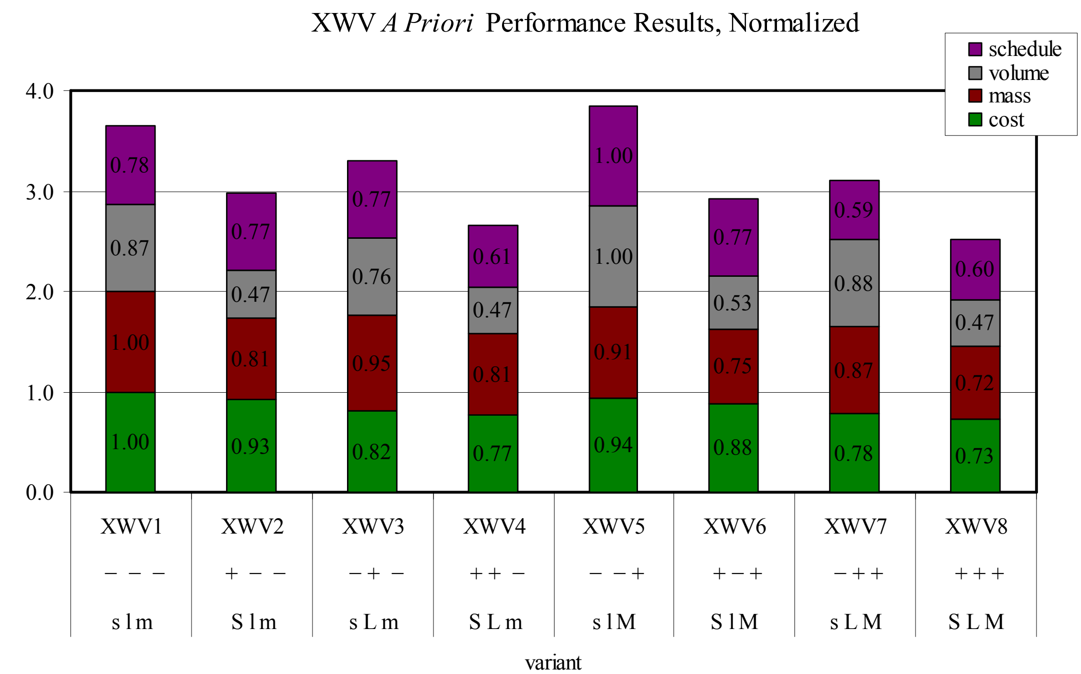


Figure 55: XWV *a priori* performance results, normalized.

4.4.1 UT Austin ROTC Cadet Operator Population

The final group of operators consisted of 14 cadets (N = 14; 10 males, 4 females).[187] Of these, four cadets had prior combat experience, having served as enlisted soldiers prior to joining the ROTC program. All test subjects had driver's licenses indicating experience operating wheeled vehicles. Notably, there was great diversity in gaming experience, ranging from minimal weekly participation (seven cadets) to greater than 20 hours per week (two cadets). Figure 56 depicts the self-reported weekly gaming participation for the test subject population.

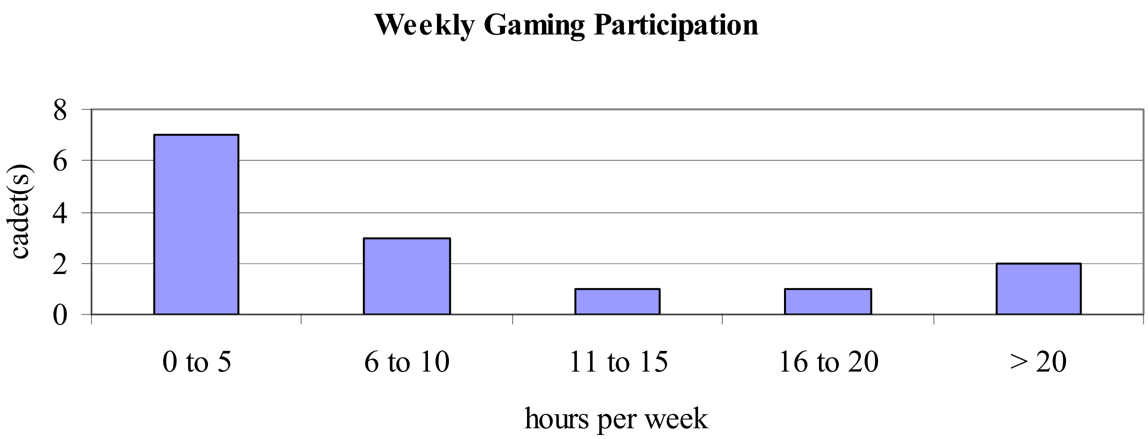


Figure 56: Weekly gaming participation (self reported) of 14 operators.

Regardless of their gaming interest or proficiency, the adherence to the eight-step training model using the "crawl-walk-run" methodology ensured that all subjects were at an acceptable level of system aptitude prior to beginning the experiment. This was verified with thorough screening of the record training missions in a stage-gate process. The test protocol had each operator conduct 15 missions on 10 randomly assigned platforms (two training vehicles, four tracked vehicles, and four wheeled vehicles)

[187] Of the original 16 cadets recruited, two had last-minute conflicts that prevented their participation.

providing overlapping coverage and resulting in data for over 1,600 missions (approximately 100 missions per vehicle). The workstation vehicle assignment matrix is provided in Appendix 13.

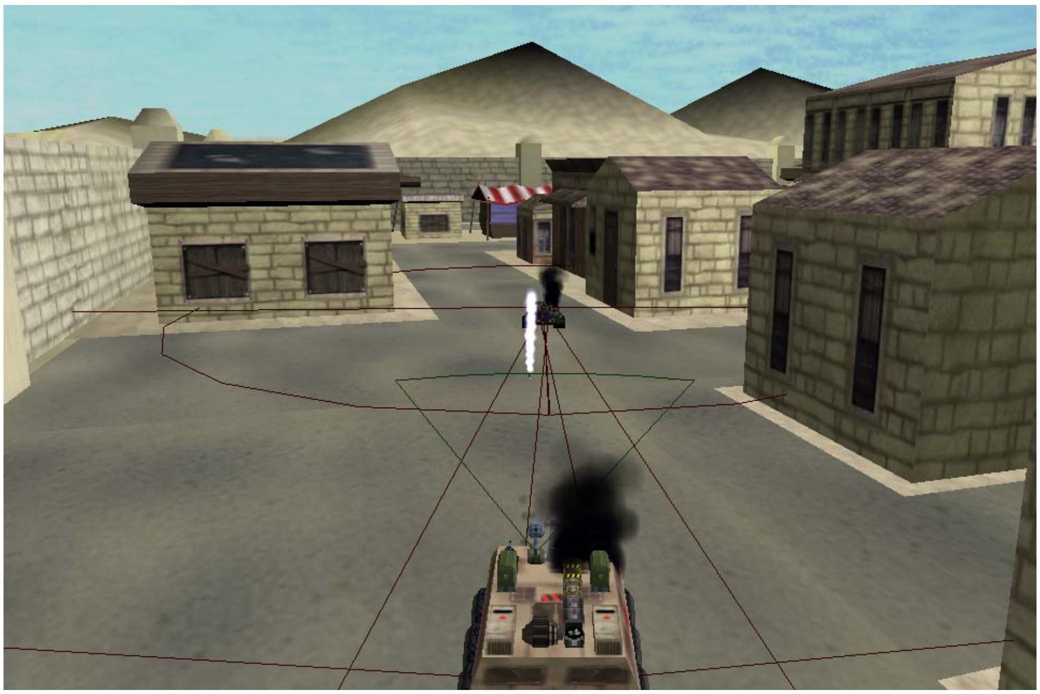


Figure 57: JRATS screenshot during contact with enemy. Note smoke signatures from previous insult, as well as the incoming missile from the threat vehicle.

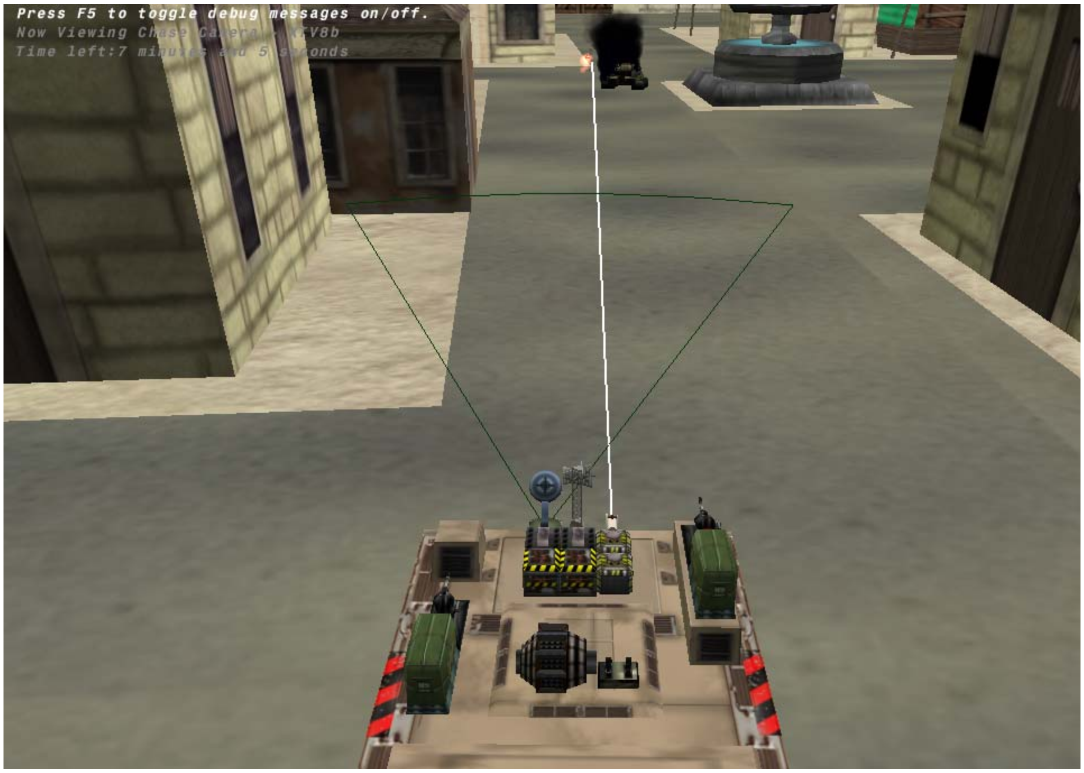


Figure 58: JRATS screenshot during contact. In this shot, the guided missile has drifted left of the laser and has missed the threat vehicle.

4.4.2 Experimental Tracked Vehicle (XTV) Results and Observations

The first 800 missions were conducted on the experimental tracked vehicles, XTVs 1–8. The results of these missions are summarized in Figure 60. These results are also normalized in Figure 61 with respect to the best performer for each metric. Since the objective is to minimize the red % and time %, these two performance metrics were normalized with respect to the minimum (best) variant value, then subsequently inverted. For example, the variant with the lowest value for time % scored a 1.0 on this adjusted scale.

The XTV summary figures are followed by sequence-related figures displaying the attribute effects and interactions in greater detail. For each of the eight performance metrics (four *a priori* and four *a posteriori*), a Pareto chart with supporting observations, as well as attribute interaction graphs with observations, are provided. The column adjoining the interaction charts includes a narrative and type classing of the attribute effects and relationships. Once again, an attribute within parentheses indicates a negative effect toward the performance metric. Moreover, if the attribute is followed by a σ, then it passed with an ANOVA F-test with at least 90% confidence. A complete summary of both XTV and XWV attribute effects, as well as an exhaustive list classifying each interaction chart by the four types previously discussed, is provided in Table 45 and Table 46. These two tables encapsulate the major observable and calculable trends from the 32 preceding figures. The referenced figures are included in column reference for each attribute and observed interaction.

A catalog of component weights and costs was also compiled in order to produce a variant breakdown of mass and cost by attribute. Mass values were elicited from the JRATS design software; commensurate fractions of supporting mass for lethality and mobility components was calculated by virtual design of a simply supported set of parallel beams adequate enough to carry the load of the identified components. Figure 78 includes the variant cost and schedule index values, plus a composite performance value depicted as the sum of win %, blue %, red % and time %. In order to investigate the learning curve of the mission operators as a function of user platform familiarity, the variant win % was calculated and averaged for each user after just 5 missions and subsequently compared to the final average at the completion of 15 missions per operator (Figure 59). In other words, this is the average of each operator's learning curve on each respective platform.

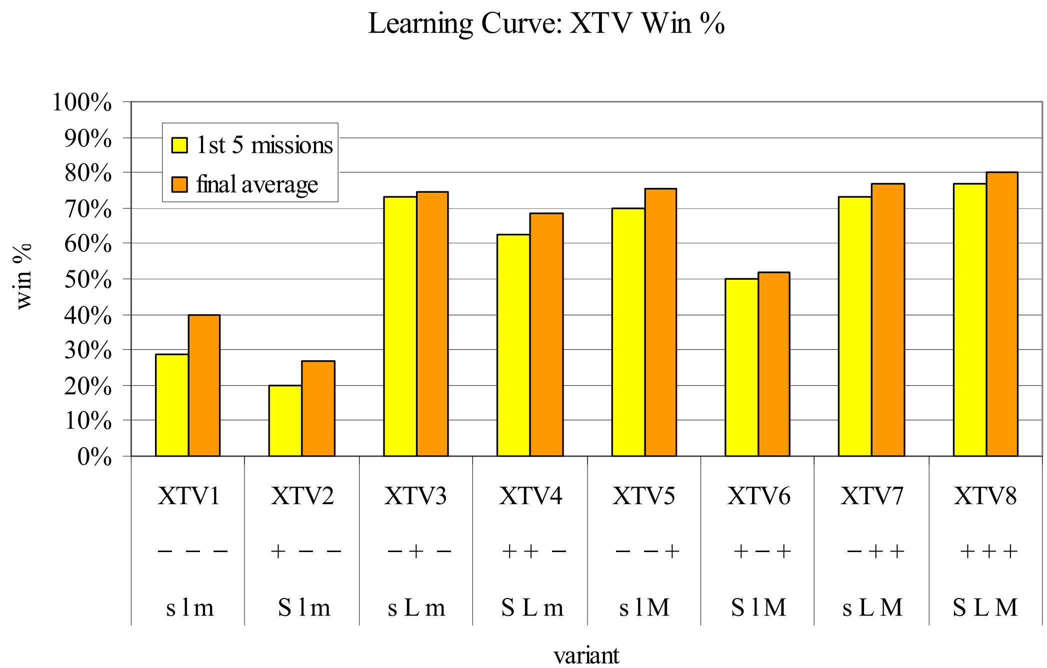


Figure 59: XTV win % learning curve. The variant performance after the first 5 missions from each operator is compared against the final average. This is the average of each operator's learning curve on each respective platform.[188]

The enhanced survivability platform had the greatest learning curve, i.e., the change in win % after the first 5 missions when compared to the final average. Since this variant had the lowest mobility performance, with no gain in lethality, operators presumably struggled initially to maneuver around the city in the mission to destroy the threat platform. Aside from the baseline variant (XTV1), all other variants had a learning curve less than 3%.

[188] In this chart, and all that follow which depict the eight variants, the sequence of pluses and minuses correspond to the level of survivability, lethality, and mobility designed into the variant. For example, a "—+" would signify acceptable levels of survivability and lethality, and an enhanced level of mobility. The letters beneath are lower case for low levels and capitalized for high levels. For example, the sequence "s L m" would indicate low levels of survivability and mobility, and a high level of lethality.

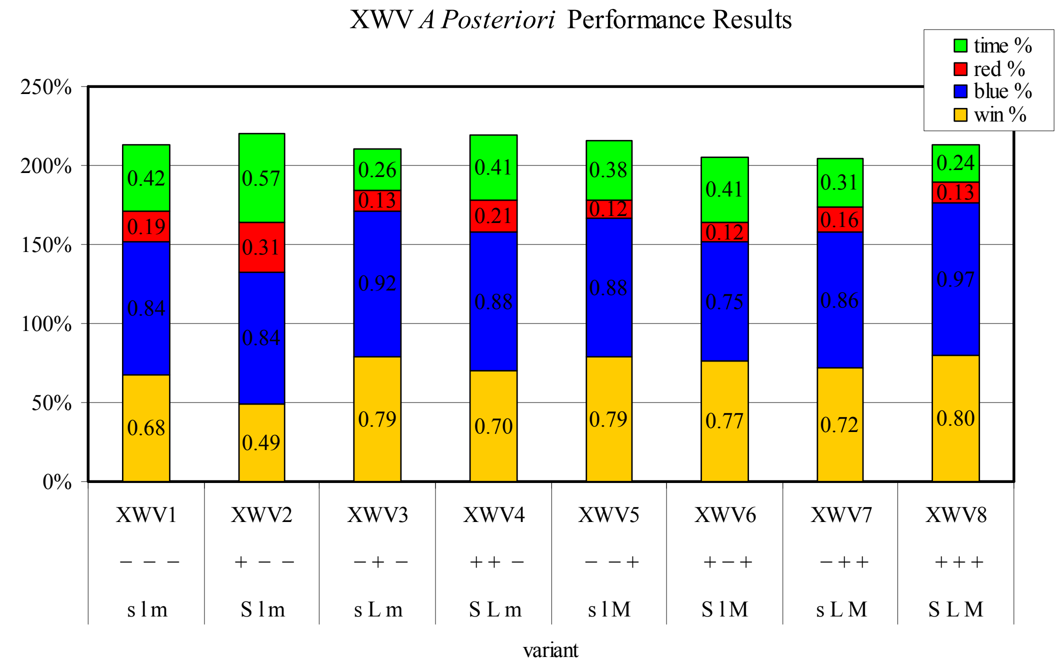


Figure 60: XTV *a posteriori* performance results with respect to time %, red %, blue %, and win %.

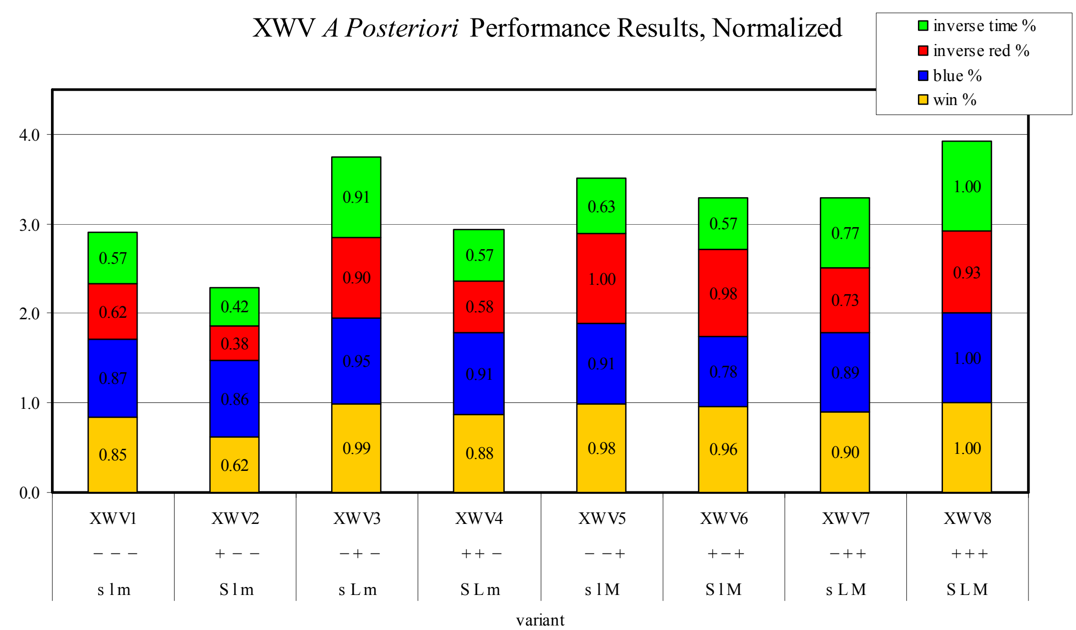


Figure 61: XTV *a posteriori* performance results normalized with respect to the best variant in each of the four performance metrics.

When the raw data from Figure 60 was normalized by the best variant in each of the four *a posteriori* performance metrics, as seen in Figure 61, several interesting observations were made. First, the top performing variants for win % all possessed enhanced levels of either lethality or mobility. Conversely, the variants possessing enhanced levels of survivability had lower win % than their numerical predecessors, with the sole exception of XTV8. Additionally, while several variants earned > 70% for win %, i.e., XTVs 3, 5, 7 and 8, enhanced lethality was conducive to a good time % performance as well. While enhanced mobility could create a win % commensurate with enhanced lethality, only lethality could also create a variant with the most competitive time % value. The decisive destruction of the threat platform, enabled by enhanced lethality, created the best win % values, while simultaneously curtailing the mission, hence good time % values. Enhanced mobility was consistently associated with variants that had good red % values. An operator of a variant with enhanced mobility and acceptable lethality was forced to adopt an attrition style of combat. This meant that the nimbleness of the platform was used to put the vehicle in a position of advantage for employment of the machine gun. Whether the mission was a win or not, this fighting style reduced the threat vehicle health rating, thereby yielding good values for red %.

An ANOVA routine, as explained previously, was done to determine the statistical significance of the effect. For any given effect (due to a single attribute or an interaction), if it passed an F-test at a 90% threshold, then that effect is followed by a σ on the appropriate Pareto figures, which illustrate the magnitude of the factor effect on the performance metric. Additionally, those attributes contributing negatively toward the metric of interest are labeled parenthetically. For example, if lethality were a statistically distinguishable factor in red %, then on the accompanying Pareto chart the respective bar would be labeled as “(L), σ”. Since the objective is to reduce the enemy’s combat power (negative trend), this means that the attribute lethality is working to reduce the enemy vehicle fighting capacity, or red %. The sigma (σ) indicates this effect passed an ANOVA routine with at least 90% significance using an F-test evaluated against tabular values.

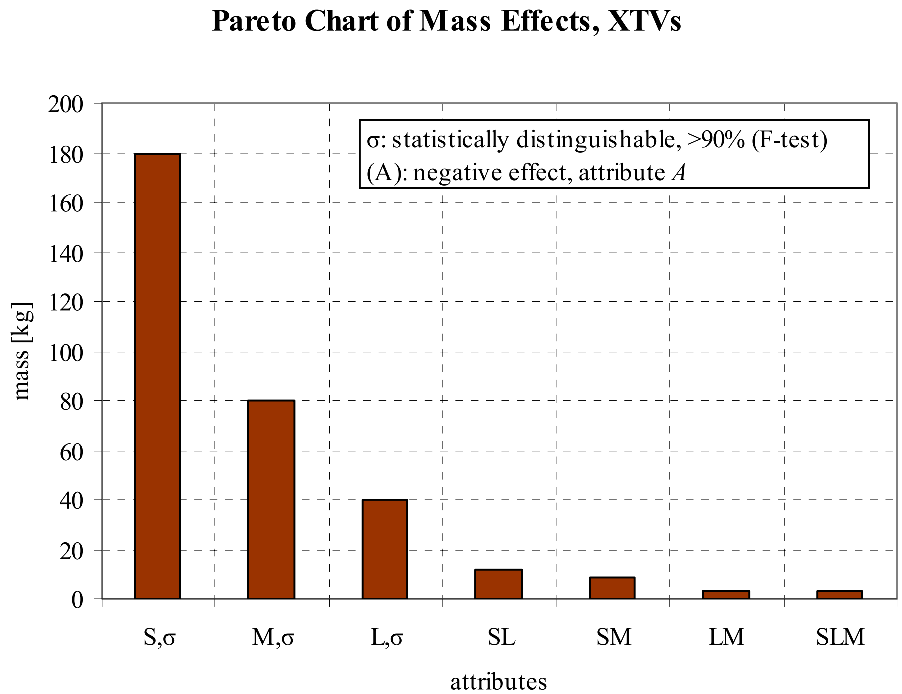
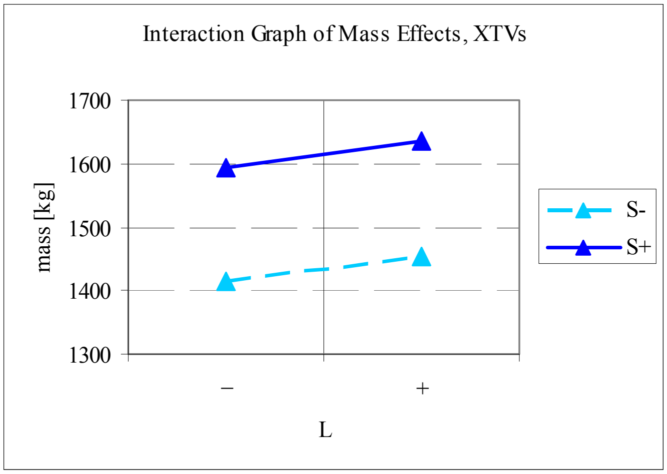
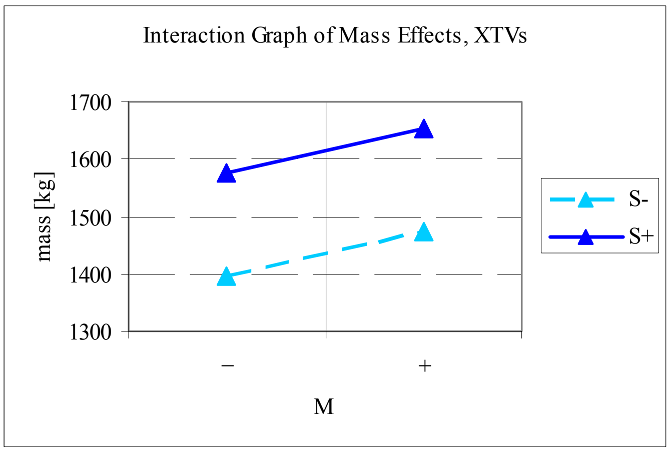


Figure 62: Pareto chart of mass effects, XTVs.

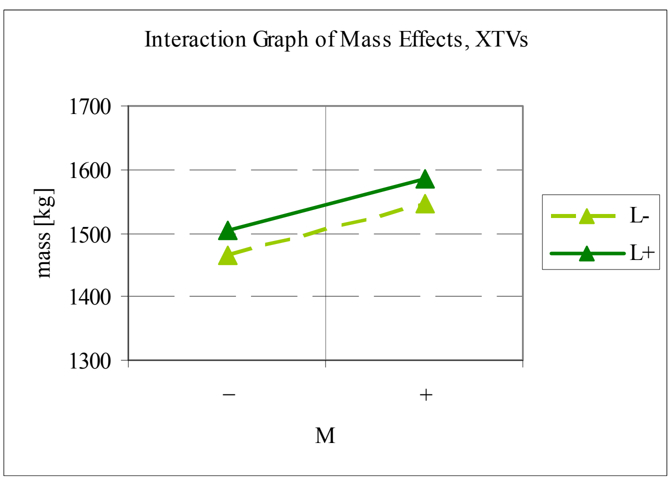
All principal attributes had a distinguishable effect on mass. Survivability had the greatest effect on increasing variant mass for the XTVs. The average increase in variant mass from acceptable to enhanced levels of survivability was 180 kg, an increase of almost 12% with respect to the average XTV gross vehicle weight. The increase in armor density and thickness, while increasing the combat survivability index, placed a noticeable large mass penalty on the variant. Mobility had the second greatest effect on increasing XTV variant mass, but with less than half the relative increase when compared to survivability (80 kg versus 180 kg). This mass increase was associated with the larger powerplant and drivetrain. Lethality had the lowest effect on XTV variant mass with a contribution of 40 kg, 4 times as low as survivability and half as low as mobility. In this simple model, no interactions significantly effected mass.



The LS interaction is a type IIc, where lethality and survivability have an effect with no interaction. The marginal for lethality (40) is positive, indicating a mass penalty for enhanced lethality. The marginal for survivability (180) is higher, indicating a greater penalty. The change in slope (0) indicates no interaction between lethality and survivability.



The MS interaction is a type IIc, where mobility and survivability have an effect with no interaction. The marginal for mobility (80) and survivability (180) are positive, indicating a mass penalty for enhanced survivability and mobility. The change in slope (0) indicates no interaction between survivability and mobility.



The ML interaction is a type IIc, where there is an effect from mobility and lethality but no interaction. The marginals for lethality (40) and mobility (80) are positive, indicating higher mass with enhanced lethality and mobility. The change in slope (0) indicates no interaction between mobility and lethality.

Figure 63: Interaction graphs of mass effects, XTVs.

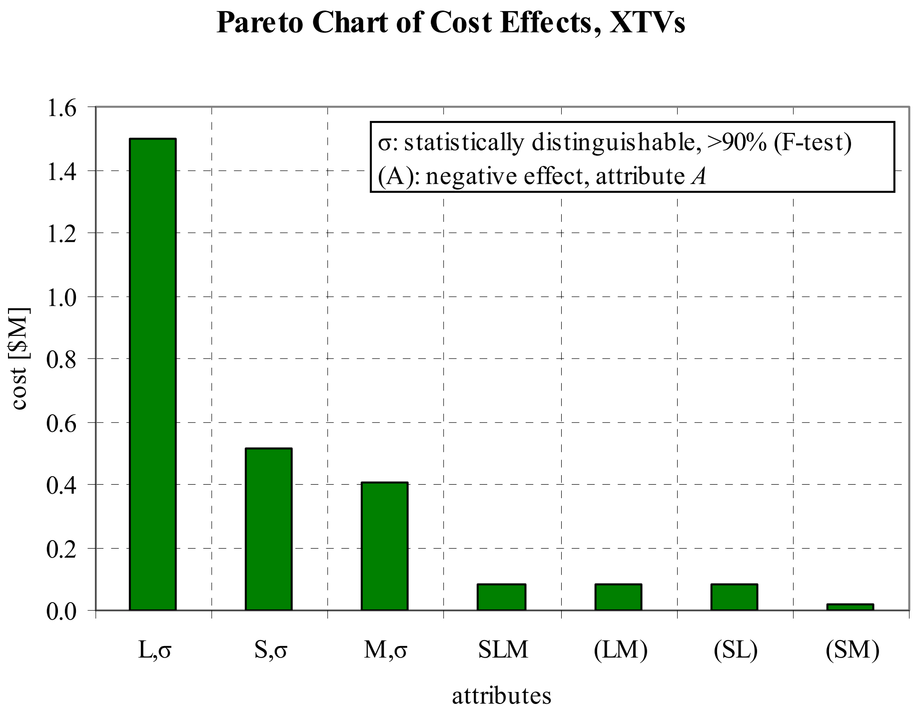
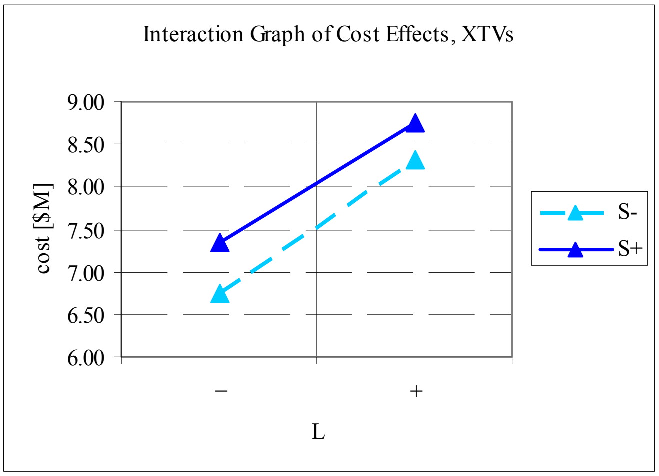
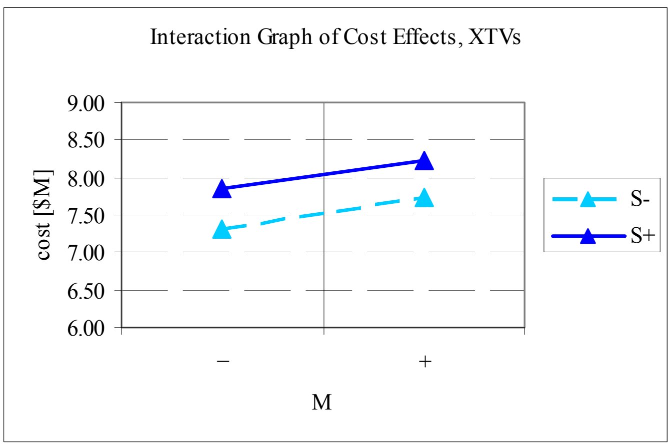


Figure 64: Pareto chart of cost effects, XTVs.

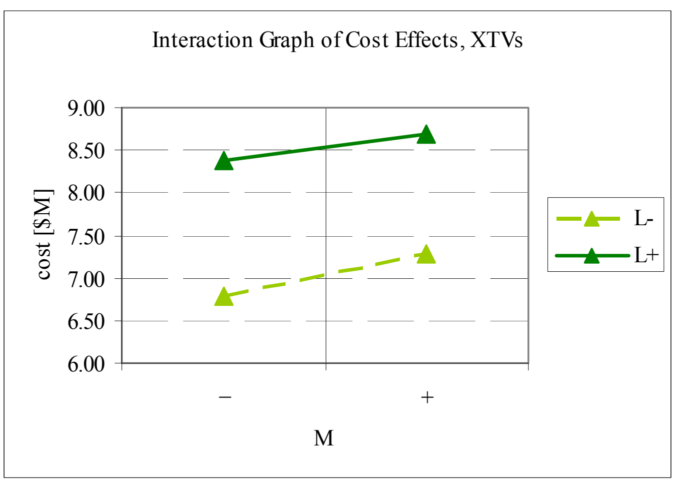
Here again, all principal attributes had a distinguishable effects on cost. Lethality had the greatest effect on increasing variant cost for the XTVs. The average increase in variant mass from acceptable to enhanced levels of survivability was nearly $1.5 million (M), an increase of almost 20% with respect to the average XTV per vehicle price tag. The high premium associated with the addition of the guided missile system was a costly upgrade that was reflected in the possession of enhanced lethality. Survivability had the second greatest effect on increasing XTV variant cost, but at only one-third the relative increase when compared to lethality ($0.52 M versus $1.5 M). Mobility had the lowest effect on XTV variant cost with an effect nearly 4 times as low as lethality. The components associated with enhanced mobility, i.e., the high output powerplant, were relatively inexpensive with respect to variant cost.



The LS interaction is a type IIc, where both lethality and survivability have an effect with no interaction. The marginal for lethality (1.5) is positive, indicating higher cost for enhanced lethality. The marginal for survivability (0.5) is lower but also positive. The small relative change in slope (0.2) indicates a low level of interaction.



The MS interaction is also of type IIc, where mobility and survivability have an effect in the absence of interaction. The marginal for mobility (0.4) and survivability (0.5) are positive, indicating a mass penalty for enhanced survivability and mobility. The change in slope (0) indicates no interaction between survivability and mobility.



The ML interaction is a type IIc, where there is an effect from mobility and lethality but no interaction. The marginal for lethality (1.5) and mobility (0.4) are positive, indicating increased cost with enhanced lethality and mobility. The change in slope is relatively low (0.1) indicating minimal interaction between mobility and lethality.

Figure 65: Interaction graphs of cost effects, XTVs.

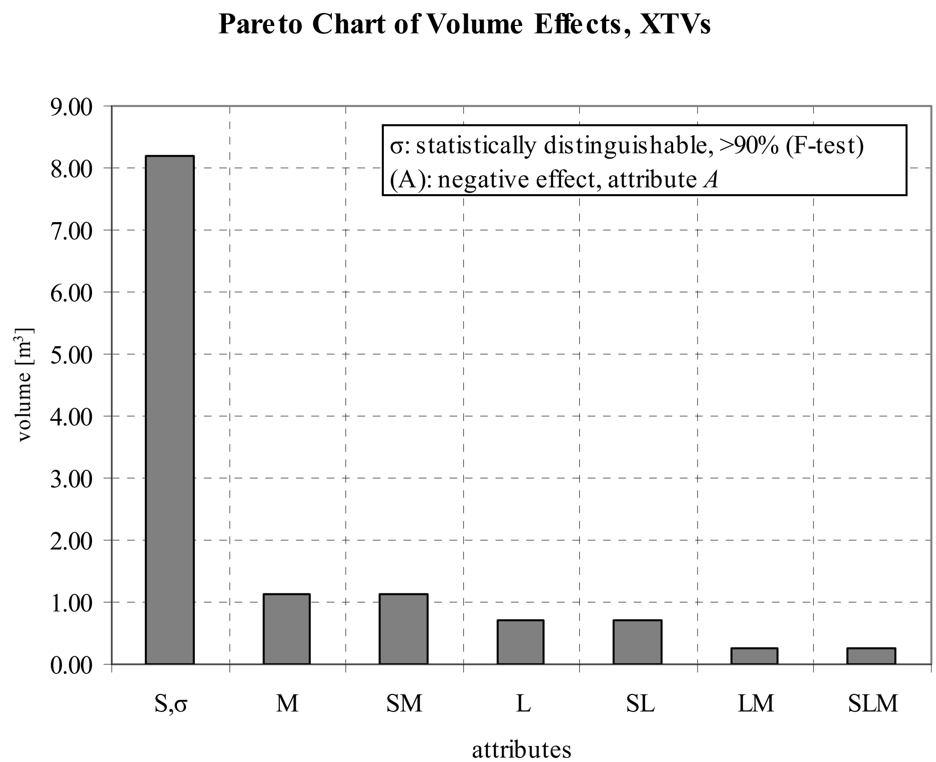
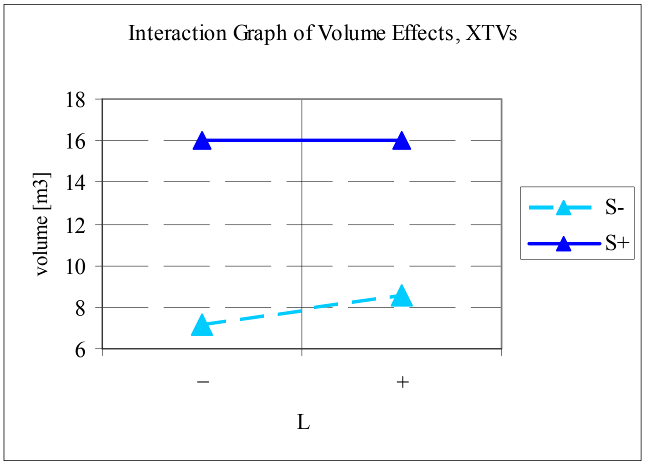
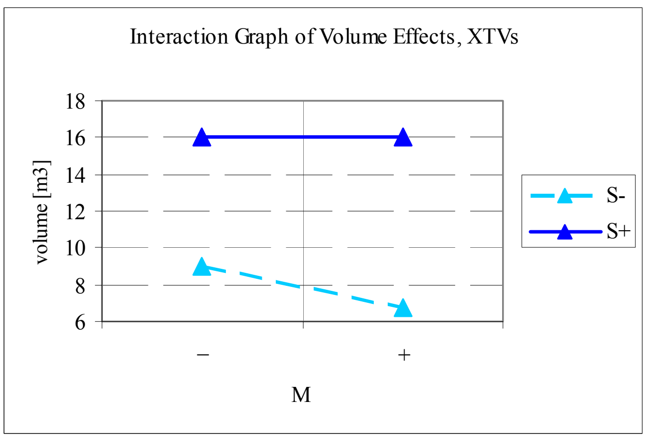


Figure 66: Pareto chart of volume effects, XTVs.

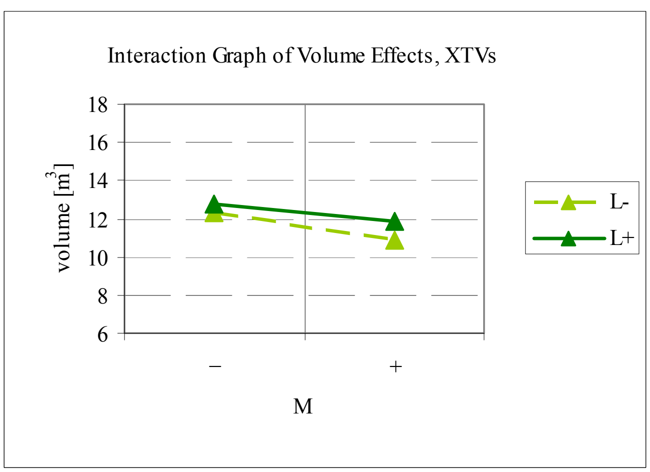
Survivability had by far the greatest and only statistically distinguishable effect on increasing variant volume for the XTVs. The average increase in variant occupied volume from acceptable to enhanced levels of survivability was more than 8 m^3, an increase over 50% with respect to the average XTV vehicle volume. The possession of an enhanced level of survivability, created by upgrading the armor material, made the platform grow substantially in length and width in order to accommodate the material and provide the increased space for the armor. Mobility and lethality trailed far behind survivability with approximately a 1 m^3 increase in variant volume associated with those two attributes. While enhanced mobility was largely internal to the structure, enhanced lethality made the vehicle grow in height to accommodate the missile launcher.



The LS interaction is a type IIa, where survivability has an effect with no interaction. The marginal for lethality (1) indicates a slight increase in volume for enhanced lethality. The marginal for survivability (8) indicates a large increase in volume for enhanced survivability. The relatively small change in slope (1) indicates no significant interaction.



The MS interaction is a type IIa, where survivability has an effect with no interaction. The marginal for mobility (-1) and survivability (8) are negative and positive, indicating a small decrease and large increase in variant volume for enhanced mobility and survivability respectively. The change in slope (2) indicates no significant interaction between survivability and mobility.



The ML interaction is a type I, where there is no significant effect from lethality or mobility. The marginal for lethality (1) and mobility (1) indicate a small penalty for enhanced lethality and mobility with respect to the variant volume. The change in slope (1) indicates minimal interaction between mobility and lethality.

Figure 67: Interaction graphs of volume, XTVs.

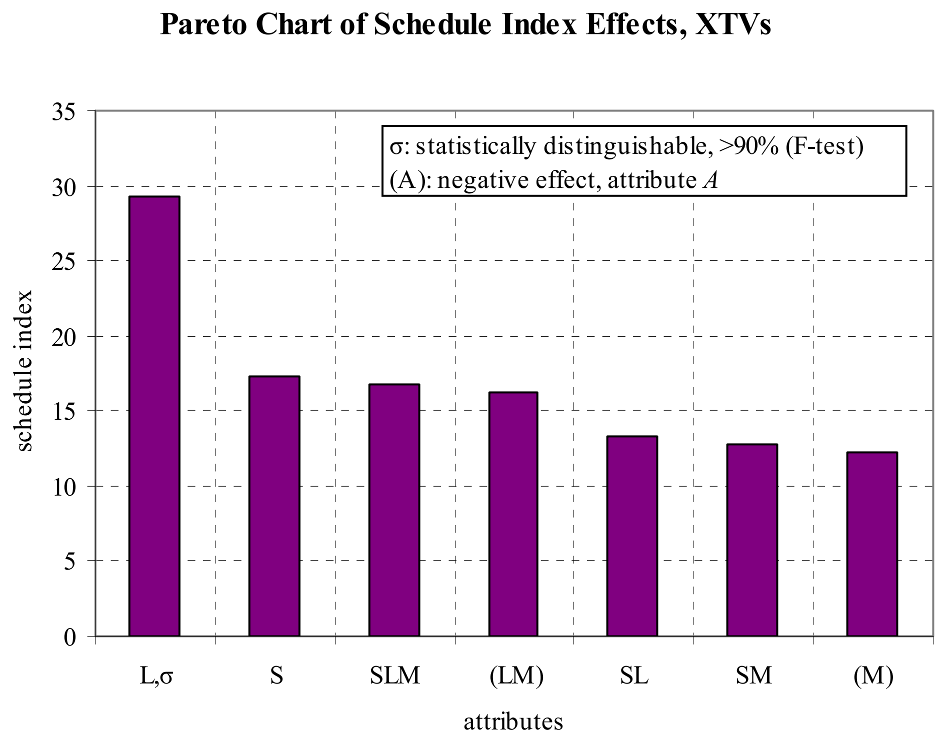
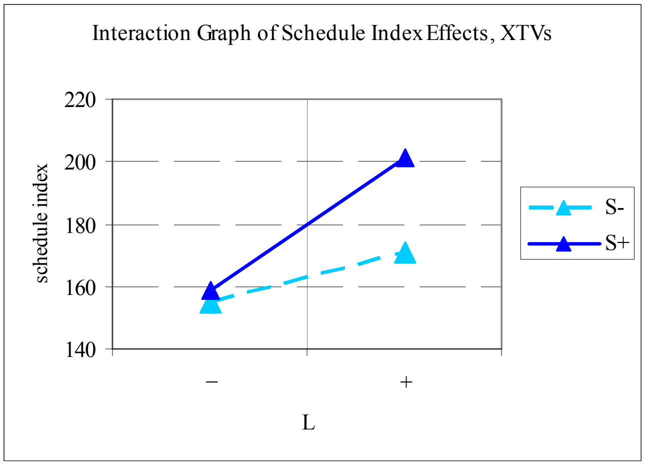
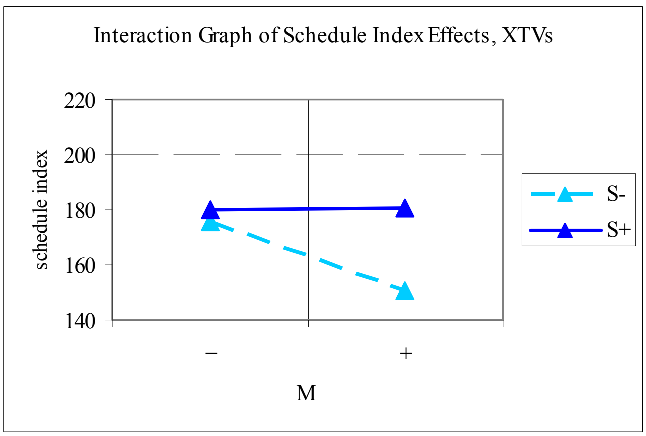


Figure 68: Pareto chart of schedule index effects, XTVs.

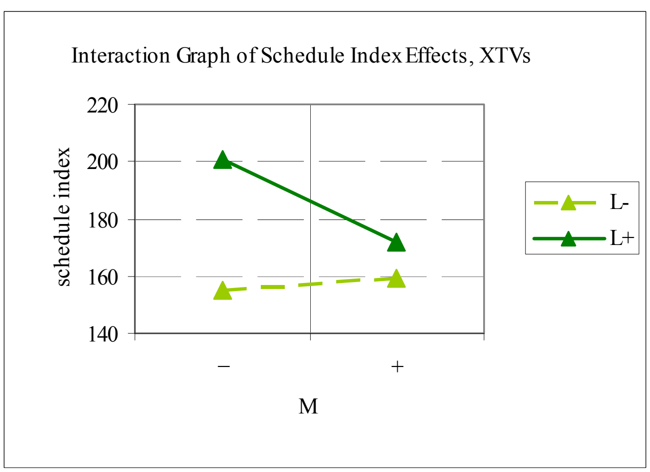
Lethality had the greatest effect on increasing schedule index for the XTVs. The average increase in variant schedule index from acceptable to enhanced levels of lethality was nearly 30, an increase of almost 18% with respect to the average XTV schedule index. Since enhanced lethality increased the developmental costs so substantially, this affected the schedule index in the same manner. Survivability was the second most expensive attribute, and this financial impact was observable with its ranking behind lethality in schedule index. The pursuit of greater survivability would incur extra manufacturing and production costs, thereby increasing the associated schedule for that attribute. Interestingly, the interaction SLM is nontrivial, albeit its origin is not currently obvious.



The LS interaction is a type IVc, where survivability and lethality have an effect as well as an interaction. The marginal for lethality (29) is positive, indicating higher schedule index for enhanced lethality. The marginal for survivability (17) indicates increased schedule index for enhanced survivability. The relative change in slope (27) indicates an interaction.



The MS interaction is a type IVb, where mobility has an effect as well as an interaction. The marginal for mobility (-12) and survivability (17) are negative and positive, indicating a decrease and increase in schedule index for enhanced mobility and survivability respectively. The change in slope (26) indicates an interaction between survivability and mobility.



The ML interaction is a type IVa, where there is an effect from lethality as well as an interaction. The marginal for lethality (29) and mobility (-12) indicate a penalty for enhanced lethality and a benefit for enhanced mobility with respect to the schedule index. The change in slope (33) indicates interaction between mobility and lethality.

Figure 69: Interaction graphs of schedule index effects, XTVs.

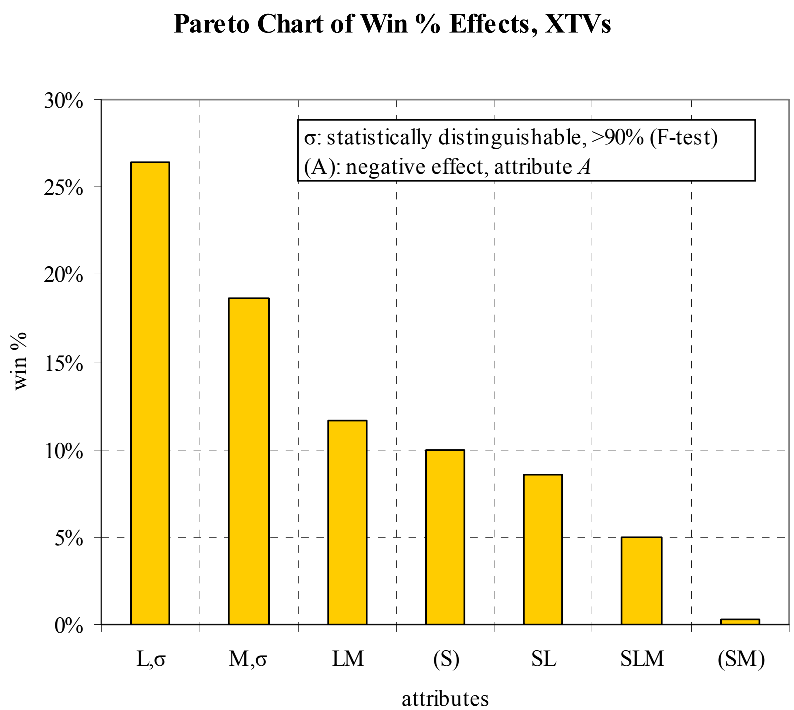
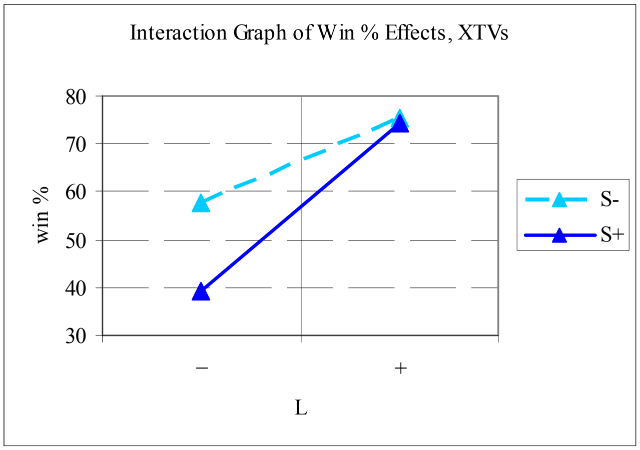
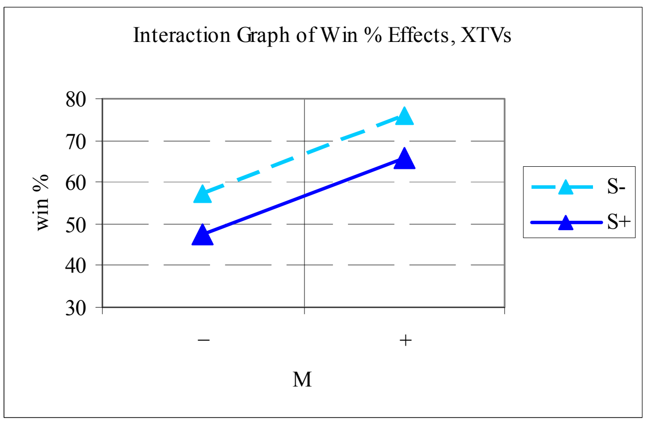


Figure 70: Pareto chart of win % effects, XTVs.

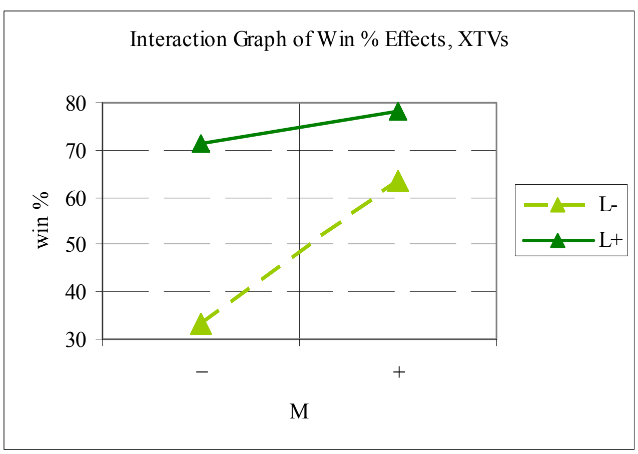
Lethality had the greatest effect on win % for the XTVs. The average increase in win % from acceptable to enhanced levels of lethality was greater than 26%. With respect to the average XTV win %, this is an increase of nearly 42%. The increased firepower associated with enhanced lethality yielded a weapon system that could destroy the threat in two shots, versus a persistent engagement over a long duration required with the acceptable level of lethality. Mobility ranked expectedly high, as the effect of enhanced movement contributed to dominant maneuver on the threat system. The average increase in win % index from acceptable to enhanced levels of mobility was nearly 19%. While the interaction between lethality and mobility was not statistically distinguishable in this simulation exercise, these two attributes that combine to create the vital military capacity to conduct maneuver, clearly combined to improve win %. Notably, survivability had a negative effect on win %, presumably because it hampered mobility.



The LS interaction is a type IVc, where both lethality and survivability have an effect as well as an interaction. The marginal for lethality (26) is positive, indicating a beneficial trend with enhanced lethality. The marginal for survivability (-10) is negative, indicating a penalty for enhanced survivability. The change in slope (17) indicates an interaction.



The MS interaction is a type IIc, where there is an effect from mobility and survivability but not much interaction. The marginal for mobility (18) is positive, indicating a beneficial trend with enhanced mobility. The marginal for survivability (-10) is negative, indicating a penalty for enhanced survivability. The change in slope (0.5) is minimal, indicating a low level of interaction.



The ML interaction is a type IVd, where there is an effect from both attributes as well as an interaction. The marginal for both mobility (18) and lethality (26) are positive, indicating a benefit in enhanced lethality and mobility. The change in slope is also high (23) indicating an interaction between mobility and lethality.

Figure 71: Interaction graphs of win % effects, XTVs.

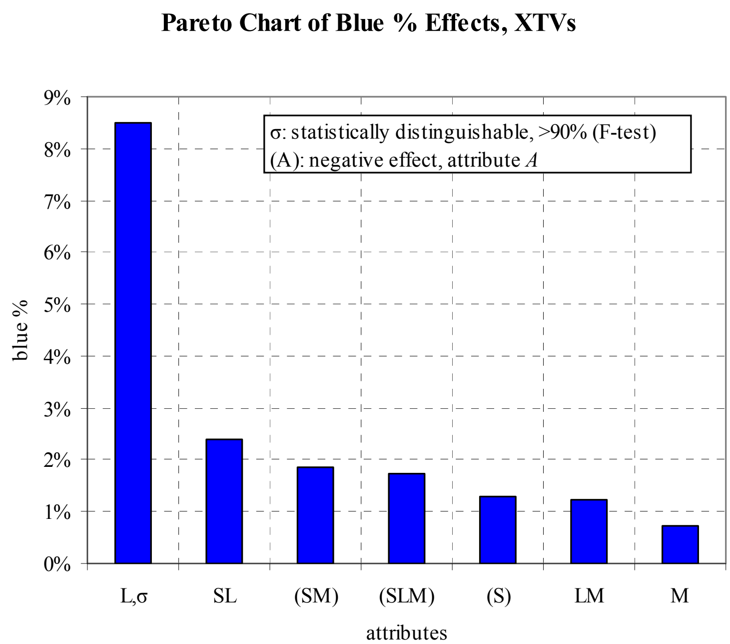
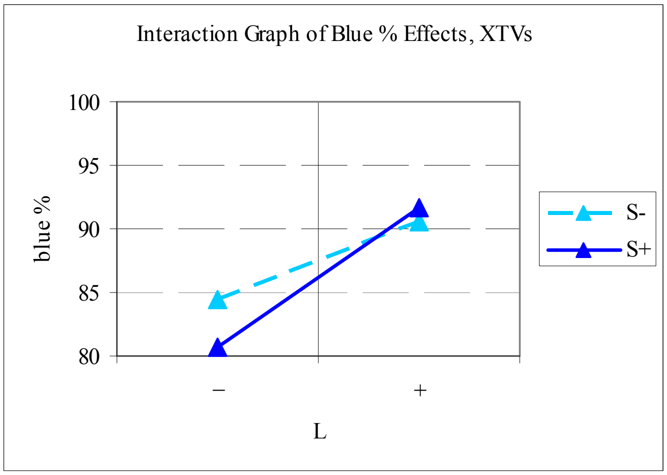
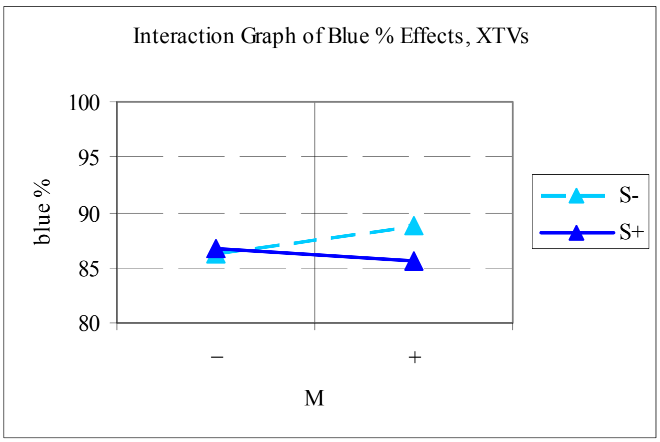


Figure 72: Pareto chart of blue % effects, XTVs.

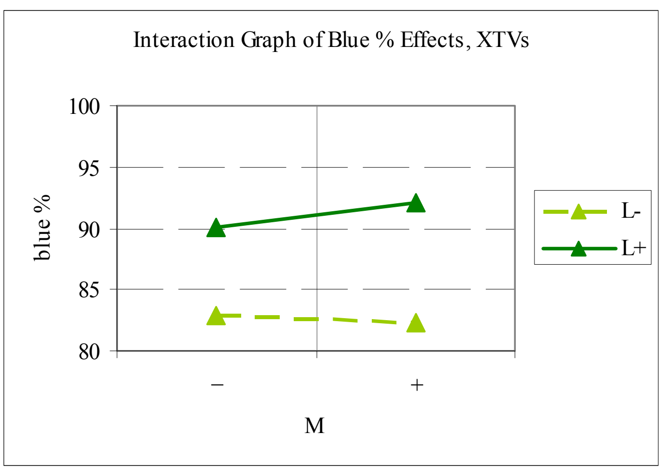
Lethality had the greatest effect on blue % for the XTVs. The average increase in blue % from acceptable to enhanced levels of lethality was over 8%. This was a surprising result, as it was expected that survivability would most greatly contribute toward better blue %. In fact, survivability had a negative effect on blue %. Contrary to initial thought, blue % was a proxy for lethality effectiveness and not survivability effectiveness. However, when survivability was added to an already lethal platform, it appeared to have a beneficial effect. With respect to the average XTV value, lethality improved blue % more than 9%. This single distinguished attribute had the only statistically distinguishable effect on blue % for XTVs. Lethality had an effect nearly 4 times greater than the next ranking element, i.e., the interaction effect of survivability and lethality. Since the enhanced lethality more effectively enabled the removal of the threat from the battlefield, the enemy was denied an opportunity to engage the friendly platform, thereby contributing the greatest effect to blue %.



The LS interaction is a type IVb, where lethality has an effect as well as an interaction. The marginal for lethality (9) is positive, indicating a beneficial trend with enhanced lethality. The marginal for survivability (-1) is minimal, indicating a penalty for enhanced survivability. The change in slope (5) indicates an interaction.



The MS interaction is a type IVa, where there is an effect from survivability as well as an interaction. The marginal for mobility (1) is positive, indicating a slight beneficial trend with enhanced mobility. The marginal for survivability (-1) is negative, indicating a penalty for enhanced survivability. The change in slope (3) is minimal, indicating a low level of interaction.



The ML interaction is a type IVa, where there is an effect from lethality as well as a small interaction. The marginal for lethality (9) is positive, indicating a benefit in enhanced lethality, while the marginal for mobility (1) is small, indicating meager but positive effect with enhanced mobility. The change in slope is small (3) indicating a weak interaction between mobility and lethality.

Figure 73: Interaction graphs of blue % effects, XTVs.

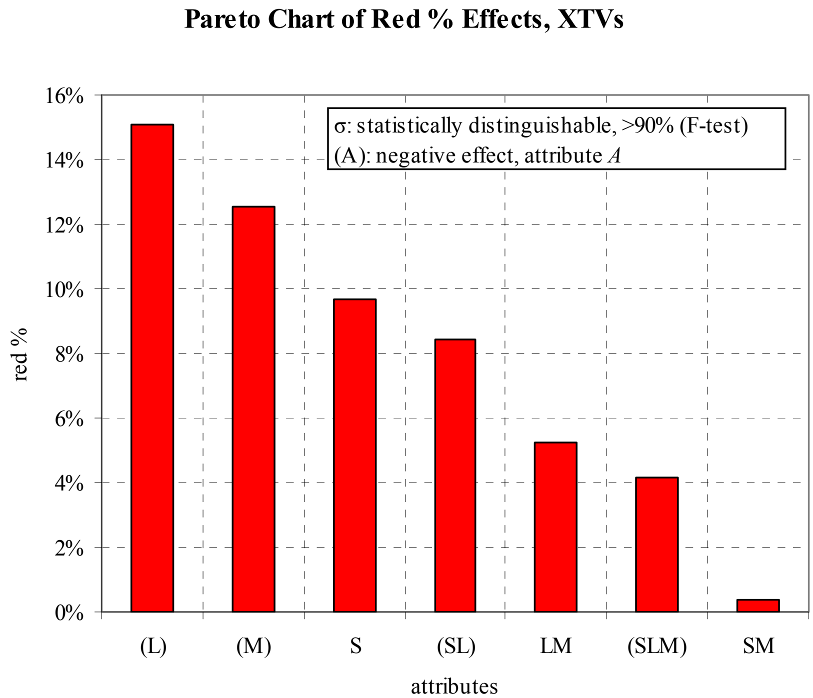
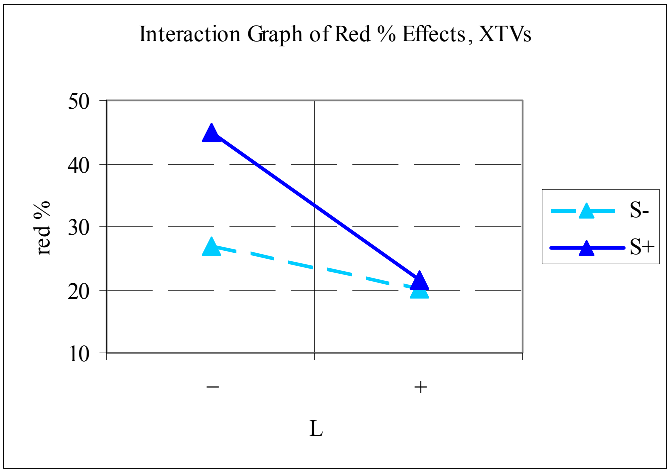
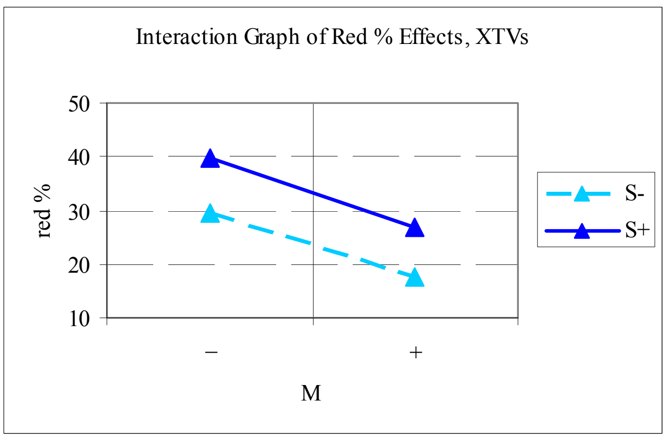


Figure 74: Pareto chart of red % effects, XTVs.

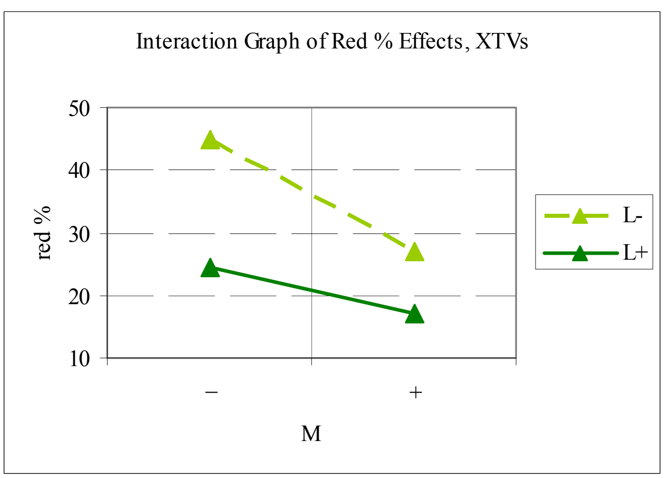
Lethality and mobility had the greatest observed effects on red % for the XTVs. The average decrease in red % (parenthetically annotated in Figure 74) from acceptable to enhanced levels of lethality was over 15%. Mobility was the next most distinguishable attribute. The average decrease in red % (parenthetically annotated in Figure 74) from low to high levels of lethality was over 12%. Both lethality and mobility contributed to a reduction in red % at nearly the same level. The fighting style of an operator with a variant possessing an enhanced level of lethality fought categorically differently than an operator with a variant possessing an enhanced level of mobility. Since each could attain the same ends, i.e., the destruction of the threat platform, the apparent distinction between these two attributes is small. Enhanced survivability had a notable negative effect on the friendly platform's ability to induce damage to the threat vehicle. The extra mass associated with this attribute diminished the ability to maneuver on the threat.



The LS interaction is a type IVc, where both lethality and survivability have an effect as well as an interaction. The marginal for lethality (-15) is negative, but this is beneficial since we desire the red health to be low. The marginal for survivability (10) is positive, indicating a penalty for enhanced survivability, i.e., higher enemy health. The change in slope (17) indicates an interaction.



The MS interaction is a type IIc, where there is an effect from mobility and survivability but no interaction. The marginal for mobility (-13) is negative, indicating a beneficial trend (lower enemy health) with enhanced mobility. The marginal for survivability (10) is positive, indicating a penalty for enhanced survivability. The change in slope (1) is minimal, indicating a low level of interaction.



The ML interaction is a type IVd, where there is an effect from lethality as well as an interaction. The marginals lethality (-15) and mobility (-12) are negative, indicating a benefit in enhanced lethality and mobility. The change in slope (10) indicates an interaction between mobility and lethality.

Figure 75: Interaction graphs of red % effects, XTVs.

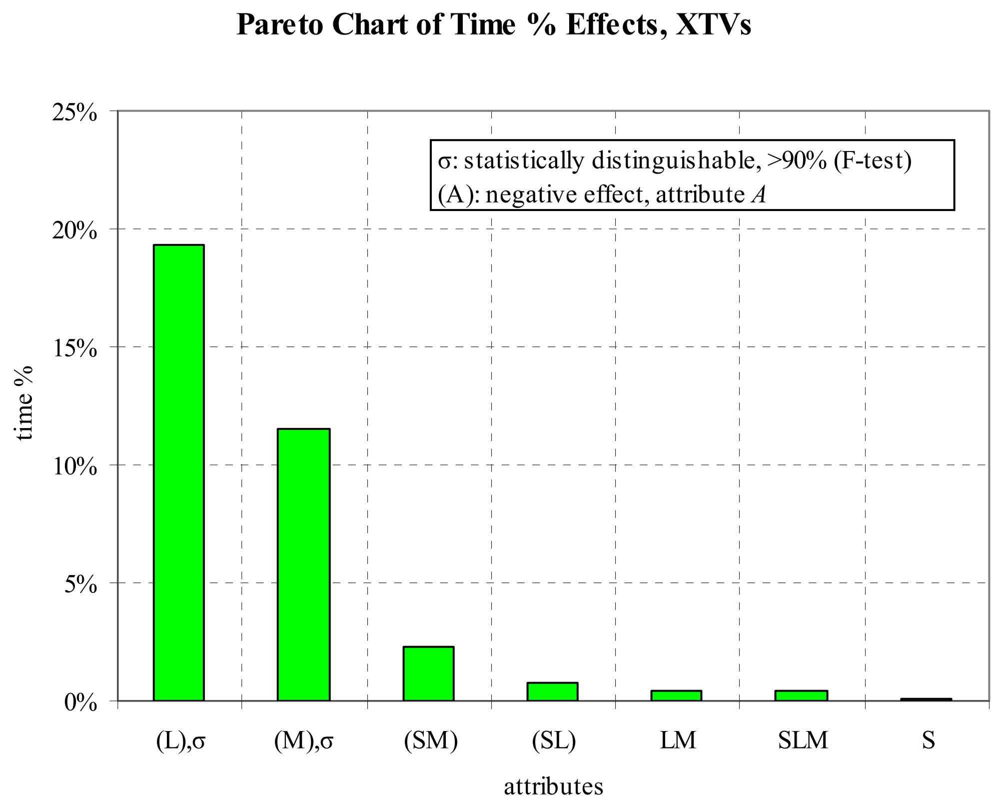
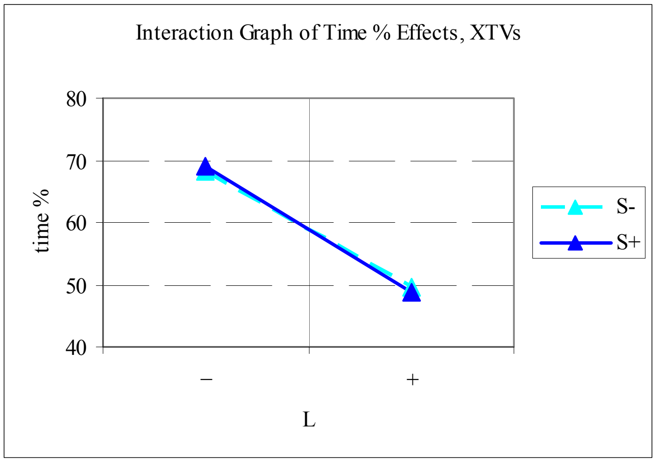
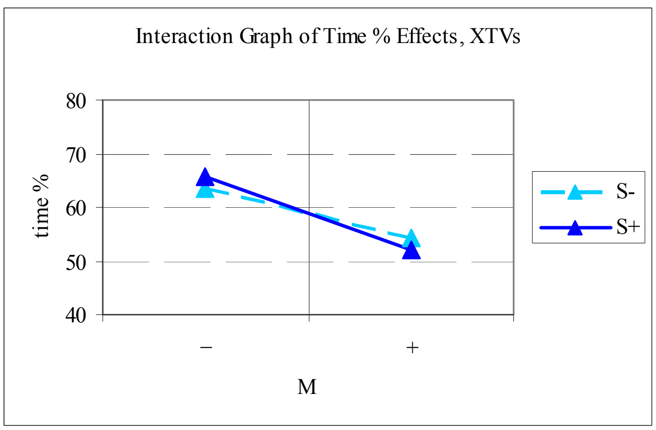


Figure 76: Pareto chart of time % effects, XTVs.

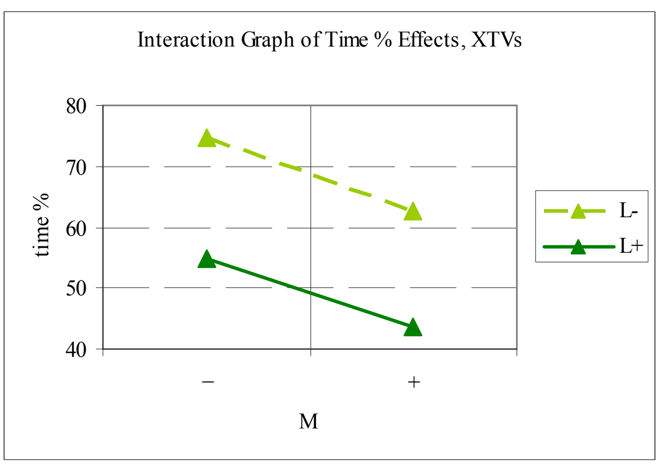
Somewhat surprisingly, lethality, not mobility, had the greatest effect on time % for the XTVs. Initially, it was thought that the enhanced mobility would afford the operator with a platform that could more quickly navigate the environment and destroy the threat. While this was generally true, the decisive factor in reducing time % was not in movement, but in destroying the threat. A platform with enhanced mobility could move faster, but the time required to persistently attrit the enemy with the acceptable weapon system was longer than that associated with the enhanced lethality weapon system. The average decrease in time % (parenthetically annotated in Figure 76) from acceptable to enhanced levels of lethality was over 19%. This is a nearly 30% reduction in mission time % with respect to the average time % for the XTV variants. Mobility was the next most distinguishable attribute with respect to reducing the time %. The average decrease in time % (parenthetically annotated in Figure 76) from acceptable to enhanced levels of lethality was over 11%. This is more than half as much of a relative reduction in time % with respect to the effect of lethality. Critically, reducing the mission time % concomitantly reduces the time the platform and crewmembers are placed at risk, as well as their attendant reliance on energy, supplied by vulnerable fuel convoys. These have direct implications at the operational level. Of all *a posteriori* metrics, time % stands out as a valuable indication of platform effectiveness. Again, dominant firepower and a nimble platform were winning characteristics for variant success.



The LS interaction is a type IIb, where only lethality has an effect with meager interaction. The marginal for lethality (-19) is negative, but this is beneficial since it is desired that the mission time be low. The marginal for survivability (0.5) is positive, indicating an inconsequential penalty for enhanced survivability, i.e., longer time. The small change in slope (2) indicates minimal interaction.



The MS interaction is a type IVb, where only mobility has an effect as well as an interaction. The marginal for mobility (-12) is negative, indicating a beneficial trend (faster time) with enhanced mobility. The small marginal for survivability (0.5) is positive, indicating a penalty for enhanced survivability. The change in slope (5) indicates interaction between survivability and mobility.



The ML interaction is a type IIc, where there is an effect from mobility and lethality but no interaction. The marginals for lethality (-20) and mobility (-12) are negative, indicating a benefit in enhanced lethality and mobility. The change in slope is low (1) indicating minimal interaction between mobility and lethality.

Figure 77: Interaction graphs of time % effects, XTVs.

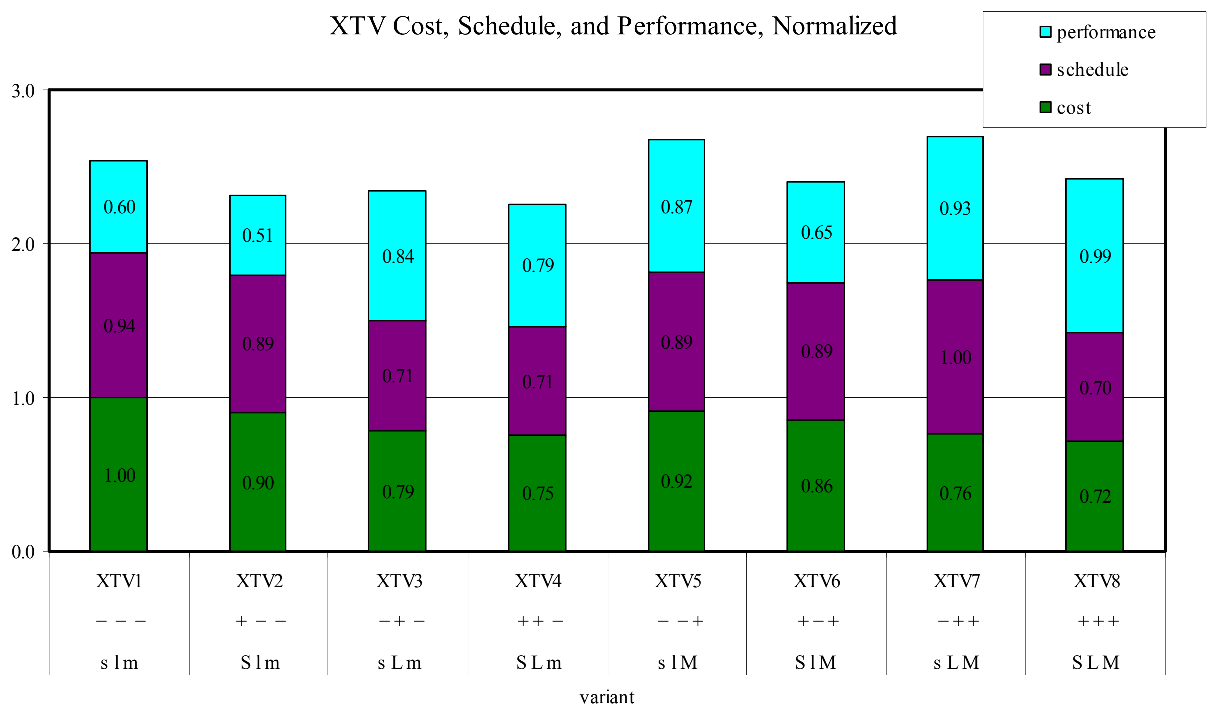


Figure 78: XTV cost, schedule, and performance (normalized by the best in category). Performance is the sum of the normalized values for variant win %, blue %, red %, and time % divided by the number of *a posteriori* metrics (4). Cost is the per vehicle cost normalized with respect to the variant with the lowest per vehicle cost. Schedule is the normalized schedule index with respect to the variant with the lowest schedule index.

When analyzing Figure 78, the cheapest variant also had the second best schedule index (XTV1). However, this variant also had the second worst performance value, where only XTV2 performed worse. The best performing variant (XTV8) was also the most expensive and had the worst schedule index. In essence, the high performance of the apex variant came at a price and with an attendant increase to the schedule index. All of the well performing candidates were also costly, given that the components associated with enhanced lethality were expensive to produce and develop. In essence, as with many pursuits, “you get what you pay for.” The categorical difference with a fighting vehicle, though, is the ultimate price a crewmember might pay for being second best. A cheap, but ineffective platform, is not really a bargain. This suggests controlling cost and schedule on a well-performing, robust candidate should be the goal.

4.4.3 Experimental Wheeled Vehicle (XWV) Results and Observations

The next 800 missions were conducted on the wheeled vehicle variants (XWVs). In identical reporting fashion to that previously presented for the tracked vehicle trials, a collection of figures followed by a similar series of Pareto charts and interaction graphs are presented. Figure 80 and Figure 81 provide a roll-up of the performance and normalized performance of the XWVs. These missions were conducted in the final 90 minutes of the five-hour experimental session. There was no apparent degradation in operator performance due to fatigue; in fact, the win % for XWVs was higher than for the XTVs (60% versus 72%). The ordering of the blocks, as well as the session duration, were initial concerns in the creation of the aggressive test matrix. Since it was assumed the tracked vehicles (XTVs) would be unfamiliar to most operators, this block was done first to benefit from the increased alertness of the respondents. In hindsight, it appears this was unnecessary since the subjects in fact recorded the best performances with the XWVs. Again, a comparative assessment of the learning curve associated with the operator and the platform was conducted after five missions and compared to the final win percentage for the wheeled variants (Figure 79).

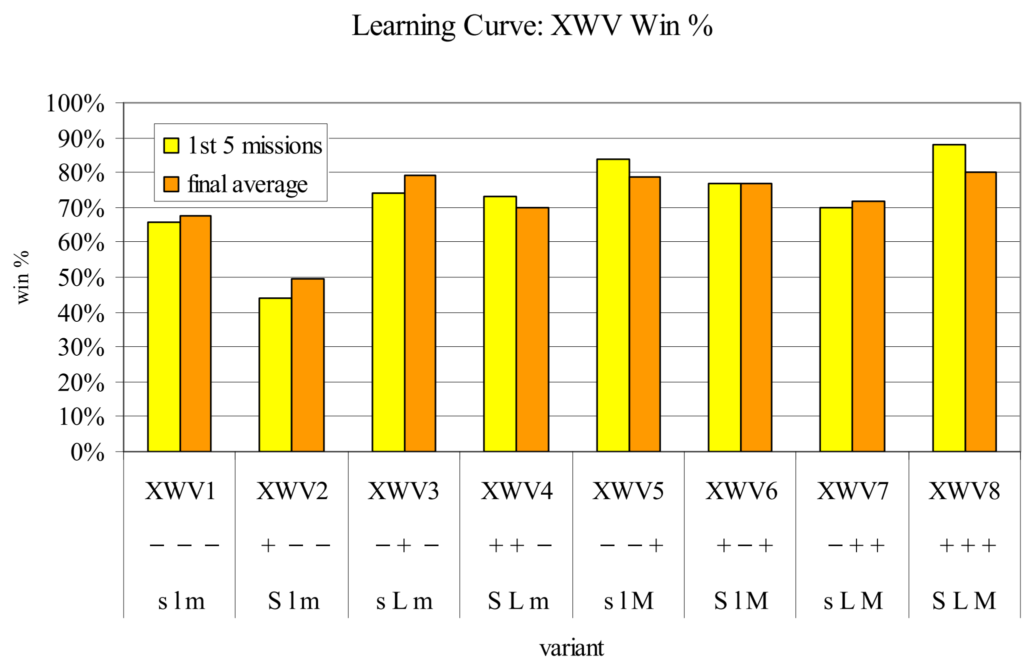


Figure 79: XWV win % learning curve. The variant performance after the first 5 missions from each operator is compared against the final average. This is the average of each operator's learning curve on each respective platform.

Similar in fashion to the results for the XTVs, the XWV learning curve was greatest for the enhanced survivability platform. Since this variant had the lowest mobility performance, with no gain in lethality, operators presumably struggled initially to maneuver around the city in the mission to destroy the threat platform. An apparent degradation in performance over time was notably different for the XWV variant results was. Most striking were the results for the apex design, XWV8, which experienced an over 5% drop in win % when the first 5 missions were compared to the final average. It may be conjectured, that the elevated baseline mobility for XWVs, enhanced even more for XWV5 and XWV8, caused operators to move in an ineffective or more "sloppy" fashion, suggesting that the platform performance is directly effected by operators.

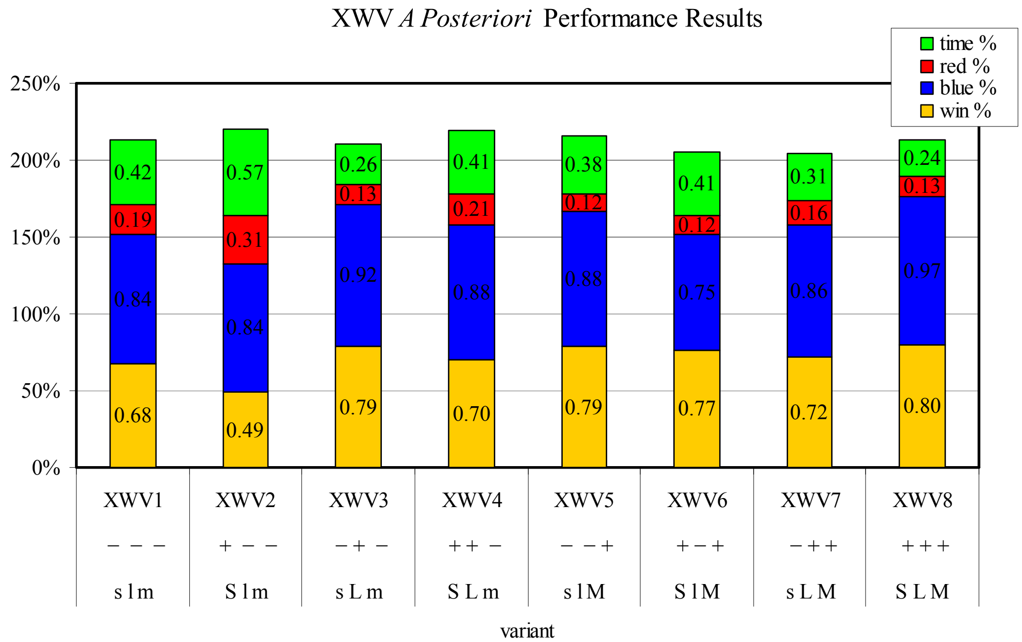


Figure 80: XWV *a posteriori* performance results with respect to time %, red %, blue %, and win %.

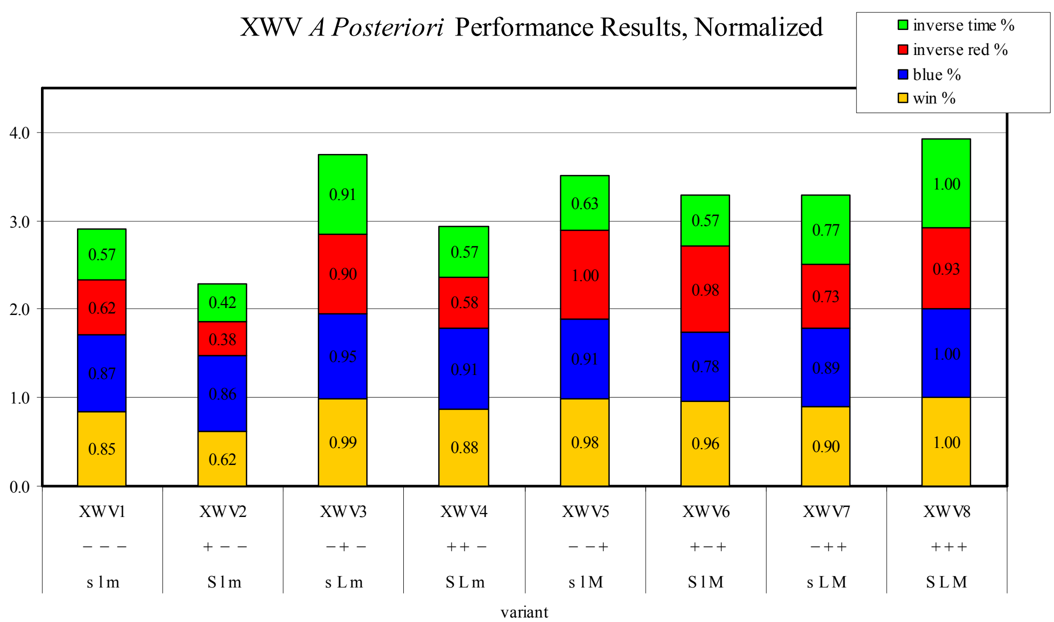


Figure 81: XWV *a posteriori* performance results normalized with respect to the best variant in each the four performance metrics.

In similar fashion to the XTV results, when the raw data from Figure 80 was normalized as seen in Figure 81, several interesting observations were made. First, the top performing variants for win % all possessed enhanced levels of either lethality or mobility. Conversely, the variants possessing enhanced levels of survivability had lower win % than their numerical predecessors, with the sole exception of XWV8. Additionally, while several variants earned > 75% for win %, i.e., XWVs 3, 5, 6 and 8, enhanced lethality was conducive to a good time % performance as well. Mobility, as an attribute, was more pronounced in effect for the XWV results, as one might expect. The wheeled variants had better baseline mobility and could attain greater performance (speed, acceleration), even under the load of enhanced survivability. Additionally, enhanced mobility could create a win % commensurate with enhanced lethality, but only lethality could also create a variant with the most competitive time % value. The deliberate attrition of the threat platform, enabled by enhanced mobility and augmented by a heavy machinegun supplied with an inexhaustible source of ammunition, created the best win % values for the XWVs, albeit with the added risk of extended mission times.

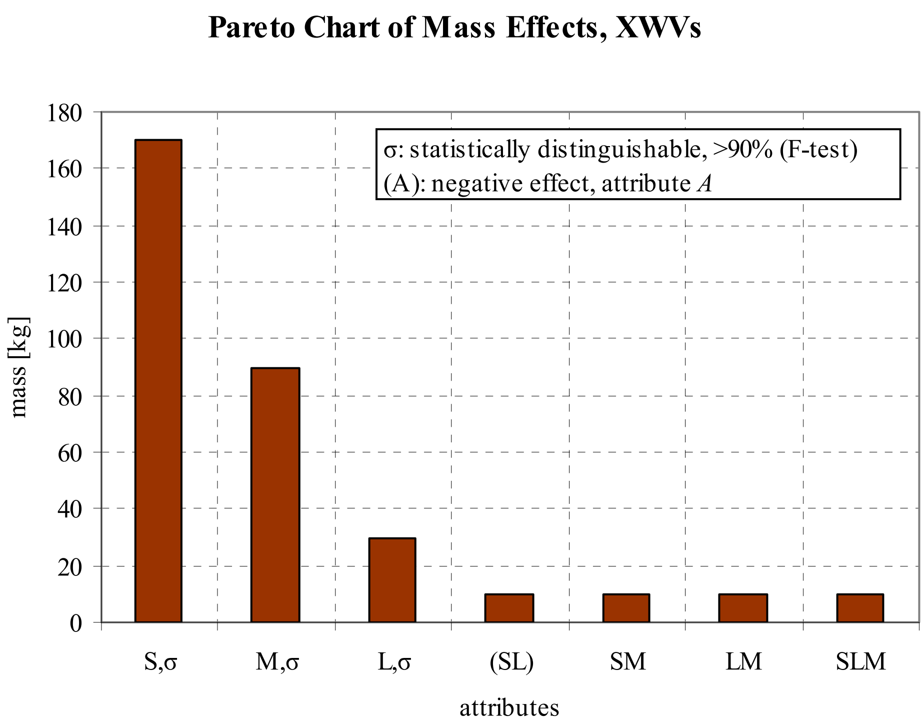
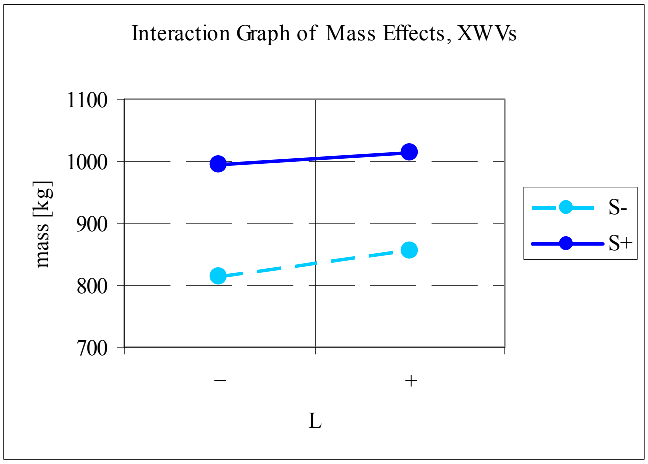
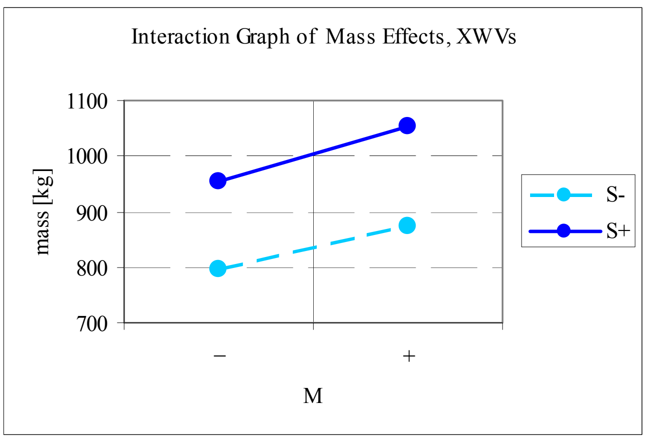


Figure 82: Pareto chart of mass effects, XWVs.

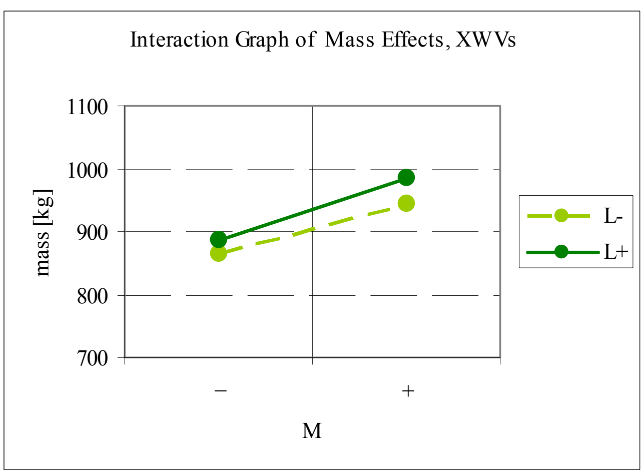
Like for XTVs, all three principal attributes had a distinguishable effect on mass. Survivability had the greatest effect on increasing variant mass for the XWVs. The average increase in variant mass from acceptable to enhanced levels of survivability was 170 kg, an increase of over 18% with respect to the average XWV gross vehicle weight, a fraction about the same as seen with the XTVs. Mobility had the second greatest effect on increasing XWV variant mass, but at more than half the relative increase when compared to survivability (90 kg versus 170 kg), here again comparable to the XTVs. Lethality had the lowest effect on XWV variant mass with a contribution 5 times as low as survivability and one-third low as mobility. Enhanced mobility, achieved with the same high output powerplant used for the XTV, had a larger fractional effect on the XWVs because the baseline mass for the XWVs was lower.



The LS interaction is a type IIc, where both lethality and survivability have an effect with no interaction. The marginal for lethality (30) is positive, indicating a penalty in mass for enhanced lethality. The marginal for survivability (170) is much higher. The small change in relative slope (20) indicates a small interaction.



The MS interaction is also of type IIc, where mobility and survivability have an effect in the absence of interaction. The marginal for mobility (90) and survivability (170) are positive, indicating a mass penalty for enhanced survivability and mobility. The change in slope (20) indicates minimal interaction between survivability and mobility.



The ML interaction is a type IIc, where there is an effect from mobility and lethality but no interaction. The marginals for lethality (30) and mobility (90) are positive, indicating higher mass with enhanced lethality and mobility. The change in slope is low (20) indicating minimal interaction between mobility and lethality.

Figure 83: Interaction graphs of mass effects, XWVs.

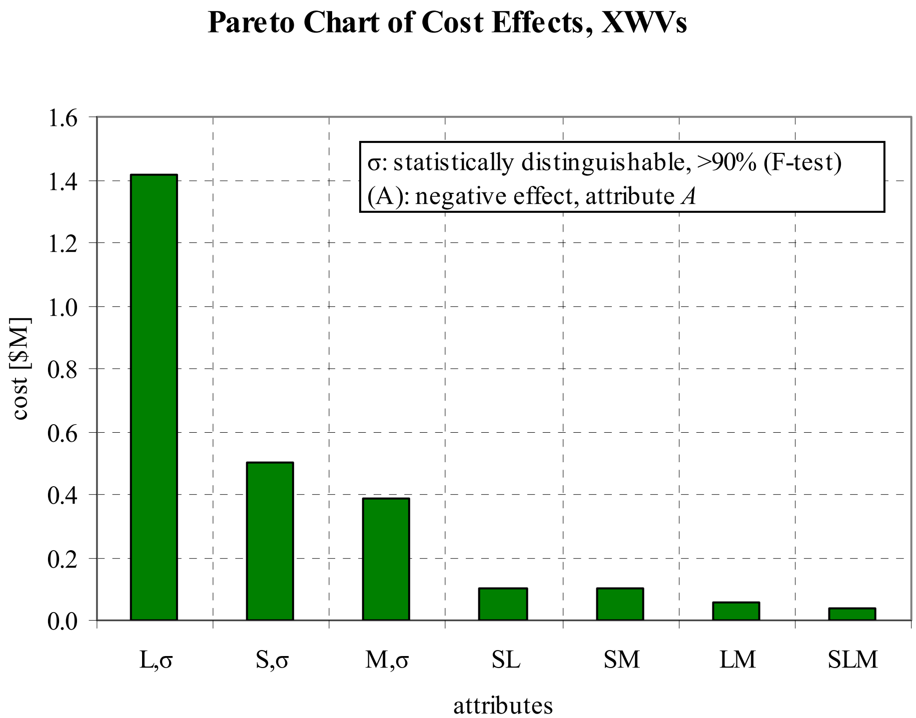
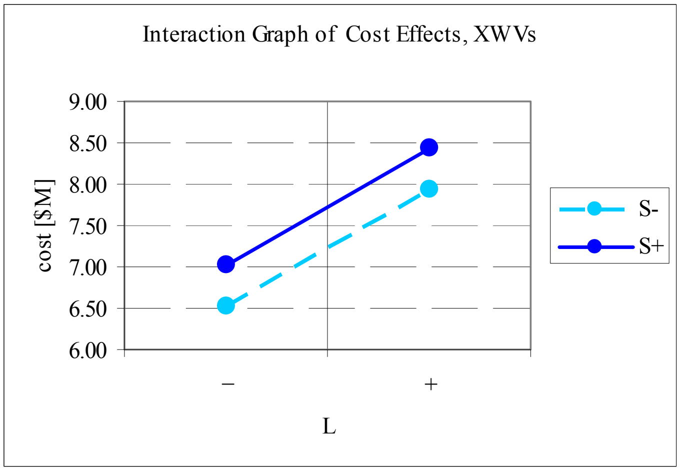
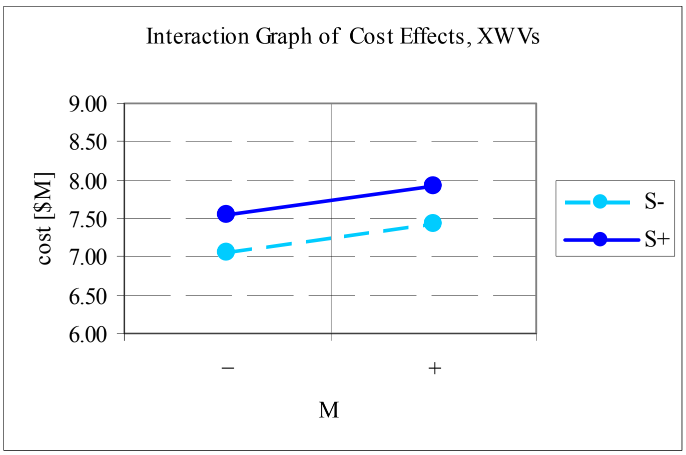


Figure 84: Pareto chart of cost effects, XWVs.

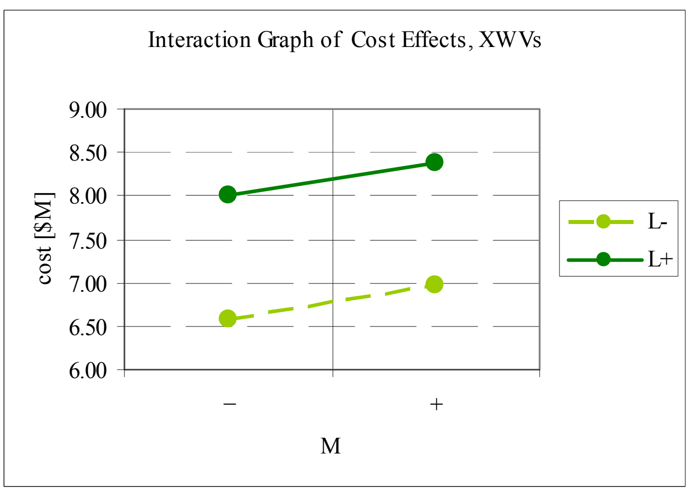
As with the results for the XTVs, all three principal attributes were statistically distinguishable with respect to XWV cost. Lethality had the greatest effect on increasing variant cost for the XWVs. The average increase in variant mass from acceptable to enhanced levels of survivability was over $1.4 million (M), an increase of almost 25% with respect to the average XWV per vehicle price tag. Survivability had the second greatest effect on increasing XWV variant cost, but at nearly one-third the relative increase when compared to lethality ($0.5 M versus $1.4 M). Mobility had the lowest effect on XWV variant cost with a contribution commensurate with lethality ($0.4 M). Here again, these values and the precedence of attributes was comparable to the XTVs.



The LS interaction is a type IIc, where both lethality and survivability have an effect with no interaction. The marginal for lethality (1.4) is positive, indicating higher cost for enhanced lethality. The marginal for survivability (0.5) is lower but also positive. The small relative change in slope (0.1) indicates a very low level of interaction.



The MS interaction is also of type IIc, where mobility and survivability have an effect in the absence of interaction. The marginal for mobility (0.4) and survivability (0.5) are positive, indicating a mass penalty for enhanced survivability and mobility. The change in slope (0.1) indicates a very low level of interaction between survivability and mobility.



The ML interaction is a type IIc, where there is an effect from mobility and lethality but no interaction. The marginal for lethality (1.4) and mobility (0.4) are positive, indicating increased cost with enhanced lethality and mobility. The change in slope is relatively low (0.1) indicating minimal interaction between mobility and lethality.

Figure 85: Interaction graphs of cost effects, XWVs.

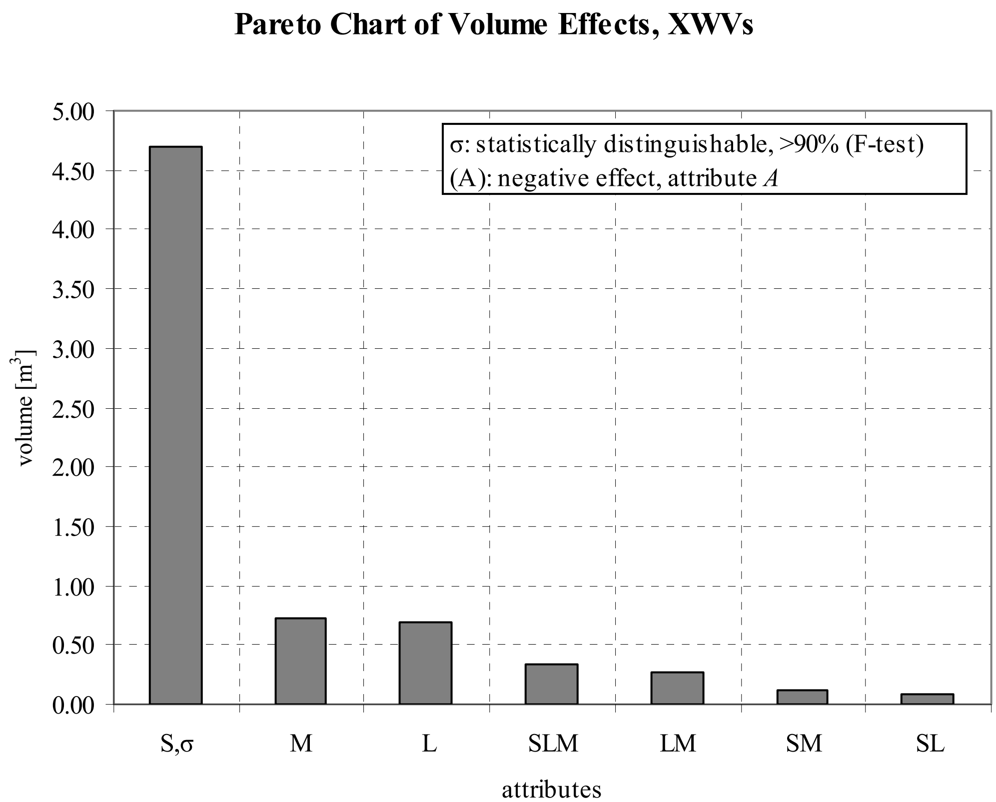
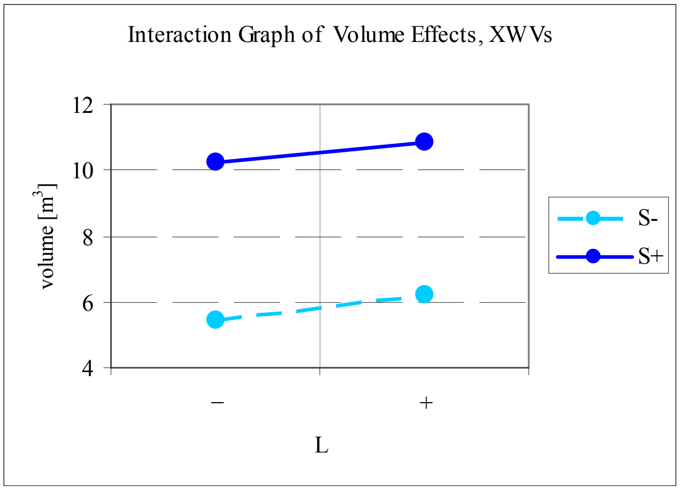
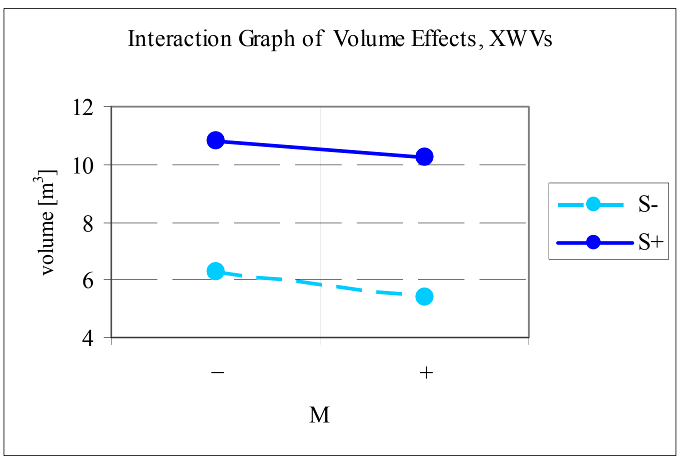


Figure 86: Pareto chart of volume effects, XWVs.

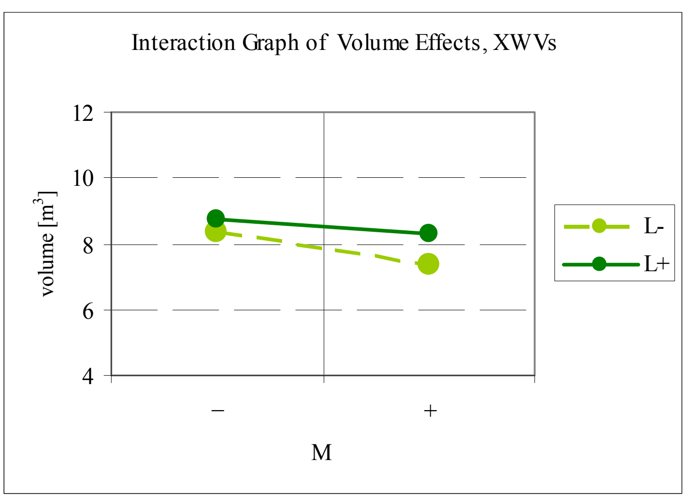
As with XTVs, survivability had by far the greatest effect on increasing variant volume for the XWVs. The average increase in variant volume from acceptable to enhanced levels of survivability was over than 4.5 m^3, an increase over 40% with respect to the average XWV vehicle volume. The XWVs were nominally smaller than the XTVs, therefore the relative increase in volume for enhanced survivability was also lower. However, the trends for attribute effects for XWV variant volume were again comparable to the XTVs. Mobility and lethality trailed far behind survivability with approximately 0.75 m^3 increase in variant volume associated with those two attributes. There were no statistically distinguishable attribute interactions observed for XWV volume.



The LS interaction is a type IIa, where survivability has an effect with no interaction. The marginal for lethality (1) indicates a slight increase in volume for enhanced lethality. The marginal for survivability (5) indicates a large increase in volume for higher survivability. The relatively small change in slope (1) indicates no significant interaction.



The MS interaction is a type IIa, where survivability has an effect with no interaction. The marginal for mobility (-1) and survivability (5) are negative and positive, indicating a small decrease and large increase in variant volume for enhanced mobility and survivability respectively. The change in slope (2) indicates no significant interaction between survivability and mobility.



The ML interaction is a type I, where there is no significant effect from lethality or mobility. The marginal for lethality (1) and mobility (1) indicate a small penalty for enhanced lethality and mobility with respect to the variant volume. The change in slope (1) indicates minimal interaction between mobility and lethality.

Figure 87: Interaction graphs of volume effects, XWVs.

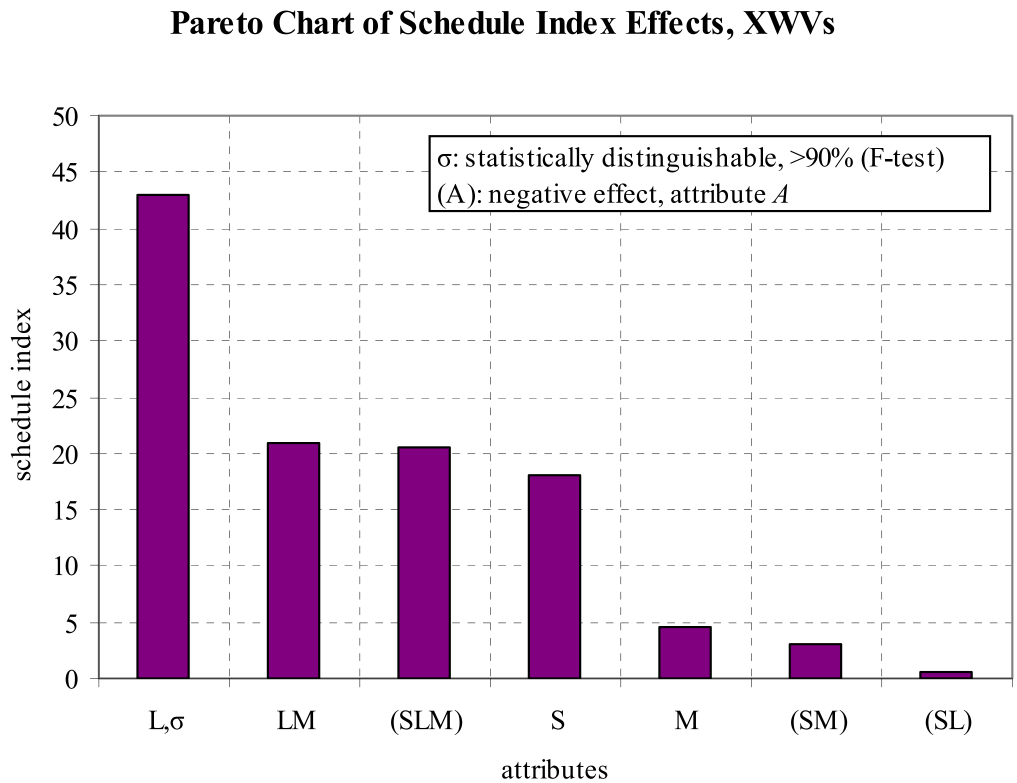
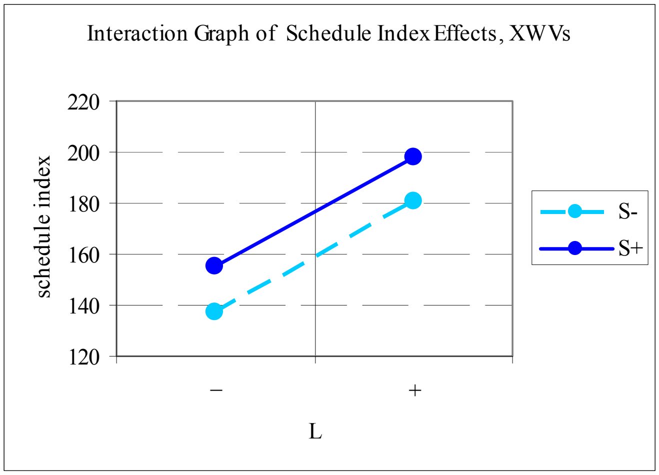
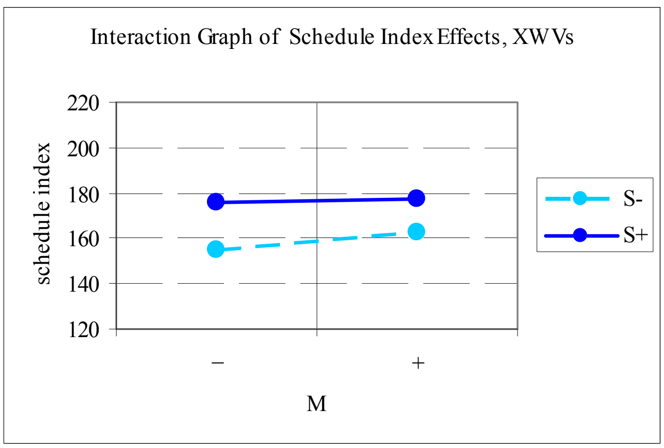


Figure 88: Pareto chart of schedule index effects, XWVs.

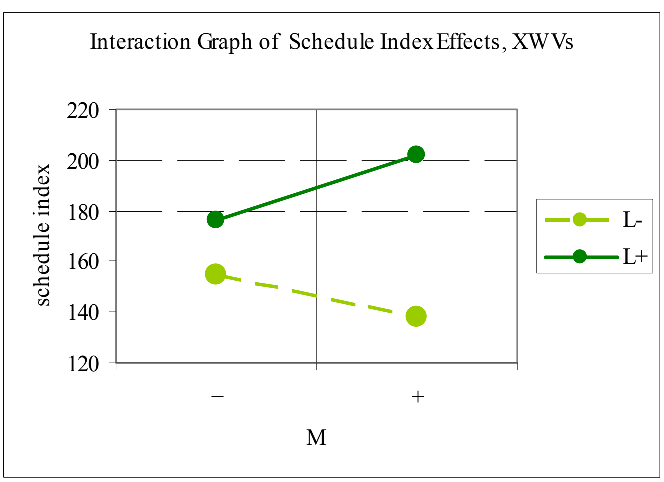
Lethality had the greatest effect on increasing schedule index for the XWVs, suggesting that particular attention should be paid to keep these components on schedule. The average increase in schedule index from acceptable to enhanced levels of lethality was nearly 43, a value greater than 25% of the average schedule index. Simultaneously pursuing enhanced lethality and mobility also adds to the schedule index. No other attribute effect, single or as a coupled interaction, had a statistically distinguishable effect on schedule index for the XWV variants. Since the nominal cost of the XWVs was less than the XTVs, but the components associated with lethality cost the same, the relative effect of this attribute was larger for XWV schedule index.



The LS interaction is a type IIc, where survivability and lethality have an effect but there is no interaction. The marginal for lethality (43) is positive, and the marginal for survivability (18) is also positive. The low relative change in slope (1) indicates insignificant interaction.



The MS interaction is of type IIa, where mobility has no effect as well as no interaction. The marginal for mobility (5) indicates a slight increase in schedule index for enhanced mobility. The marginal for survivability (18) indicates a more substantial increase in schedule index for enhanced survivability. The change in slope (6) indicates a small interaction between survivability and mobility.



The ML interaction is a type IVa, where there is an effect from lethality and interaction with mobility. The marginals for lethality (43) and mobility (5) indicate a more significant penalty for enhanced lethality with respect to the schedule index. The change in slope (42) indicates interaction between mobility and lethality.

Figure 89: Interaction graphs of schedule index effects, XWVs.

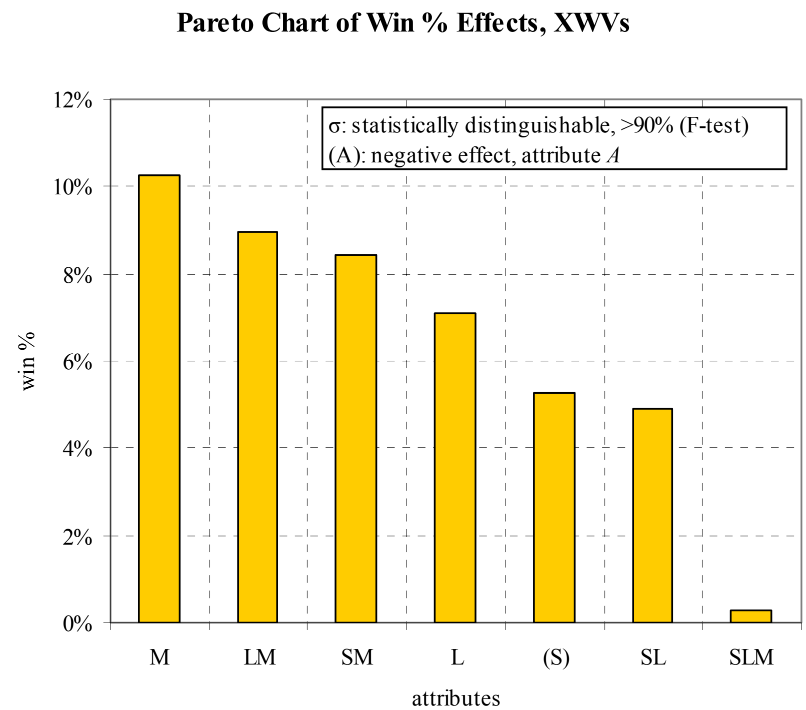
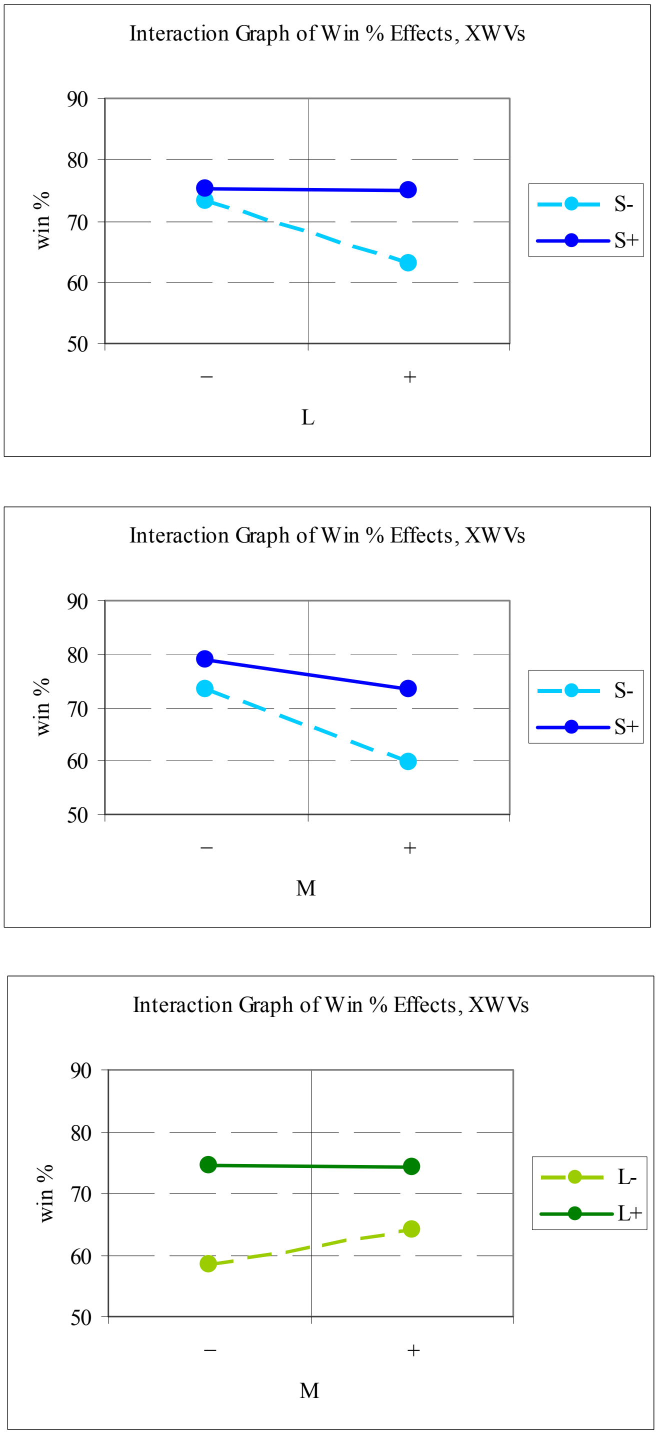


Figure 90: Pareto chart of win % effects, XWVs.

Notably, mobility, not lethality, had the greatest effect on win % for the XWVs. This is, perhaps, not surprising, given wheeled platform's intrinsically superior mobility in the urban environment depicted in the JRATS simulation. The average increase in win % from acceptable to enhanced levels of lethality was greater than 10%. The interactions between lethality and mobility as well as survivability and mobility outranked lethality in terms of commensurate level of effect on win % for XWVs, reflecting the fact that either enhanced lethality or survivability could be added to an enhanced mobility platform without deleterious effect on win %. The observed superiority of the interactions indicates that mobility had an additive effect on both lethality and survivability with respect to win %. Mobility, ranked first for XWV relative effect on win %, was ranked second for XTV relative effect on win %, right after lethality. At this point in the experiment, the operators were able to leverage a commanding knowledge of the scenario and threat vehicle patterns and create mission success with either the acceptable or enhanced lethality.



The LS interaction is a type IVc, where both lethality and survivability have an effect as well as an interaction. The marginal for lethality (7) is positive, indicating a beneficial trend with enhanced lethality. The marginal for survivability (-5) is negative, indicating a penalty for enhanced survivability. The change in slope (10) indicates an interaction.

The MS interaction is a type IVc, where there is an effect from mobility and survivability as well as an interaction. The marginal for mobility (10) is positive, indicating a beneficial trend with enhanced mobility. The marginal for survivability (-10) is negative, indicating a penalty for enhanced survivability. The change in slope (8) indicates a moderate level of interaction.

The ML interaction is a type IVd, where there is an effect from both attributes as well as an interaction. The marginals for both mobility (3) and lethality (13) are positive, indicating a benefit in enhanced lethality and mobility. The change in slope is (6) indicating an interaction between mobility and lethality.

Figure 91: Interaction graphs of win % effects, XWVs.

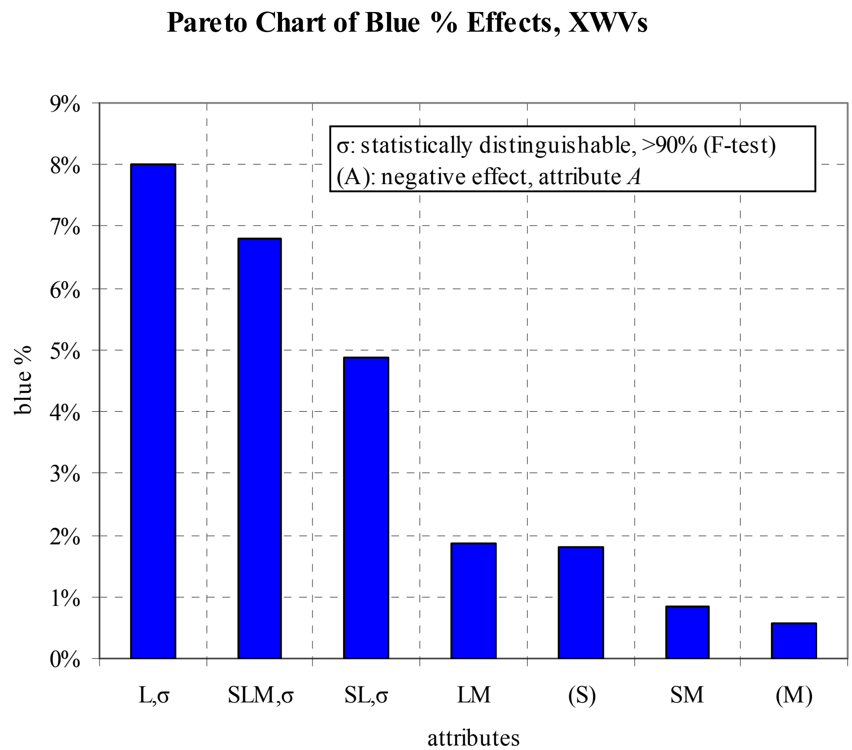
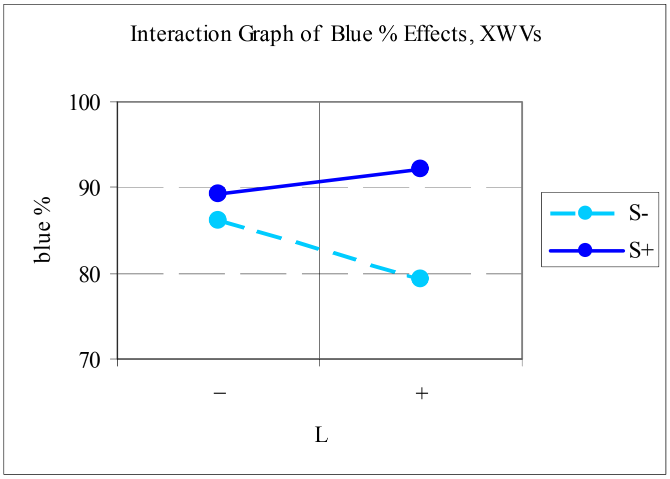
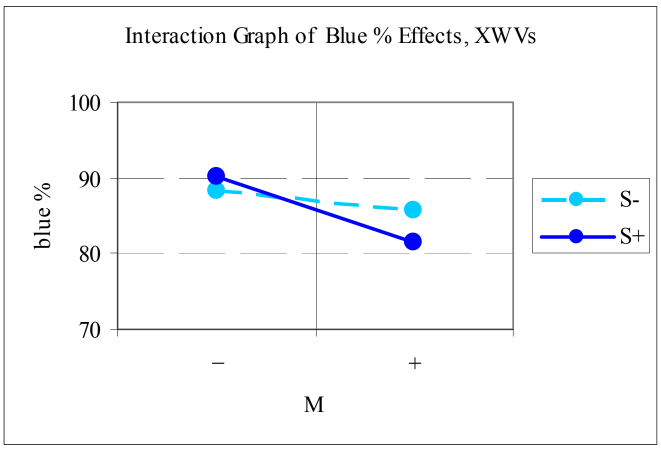


Figure 92: Pareto chart of blue % effects, XWVs.

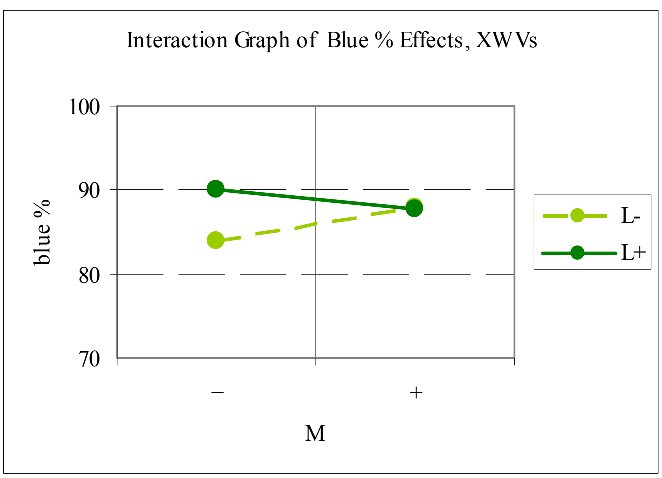
The results for XWV blue % differed the most of any *a posteriori* performance metric when compared against the XTV results. Lethality had the greatest effect on blue % for the XWVs. The average increase in blue % index from acceptable to enhanced levels of lethality was over 8%. With respect to the average XWV blue %, this is an increase of more than 9%. The interaction between all three attributes of survivability, lethality, and mobility, as well as the interaction between survivability and lethality, also had a statistically distinguishable effect on blue % for XWVs at cascading levels of under 7% and 5% respectively. The three-way interaction may be indicative of a balanced platform, one in which the attributes all contribute positively toward vehicle efficacy. Operating from a higher baseline of mobility performance, XWV blue % was positively influenced by the interaction of survivability and mobility. Since the XWV could move better even with the enhanced survivability, the extra armor had a beneficial effect on blue % but critically *only* with the complement of enhanced lethality; otherwise, enhanced survivability, on its own, had a negative effect on blue %. Similar to the results for XTVs, lethality ranked first for XWV blue %. Again, the best way to protect the friendly platform was by removing the potential for the threat vehicle to induce an insult; it was not by simply adding armor.



The LS interaction is a type IVa, where lethality has an effect as well as an interaction. The marginal for lethality (8) is positive, indicating a beneficial trend with enhanced lethality. The marginal for survivability (-2) is minimal, indicating a small penalty for higher survivability. The change in slope (10) indicates an interaction.



The MS interaction is a type IVc, where there is an effect from survivability but no significant interaction. The marginal for mobility (1) is positive, indicating a slight beneficial trend with enhanced mobility. The marginal for survivability (-3) is negative, indicating a penalty for higher survivability. The change in slope (1) is minimal, indicating a low level of interaction.



The ML interaction is a type IVa, where there is an effect from lethality as well as an interaction. The marginal lethality (7) is positive, indicating a benefit in enhanced lethality, while the marginal for mobility (1) is small, indicating meager but positive effect with enhanced mobility. The change in slope is high (8) indicating an interaction between mobility and lethality.

Figure 93: Interaction graphs of blue % effects, XWVs.

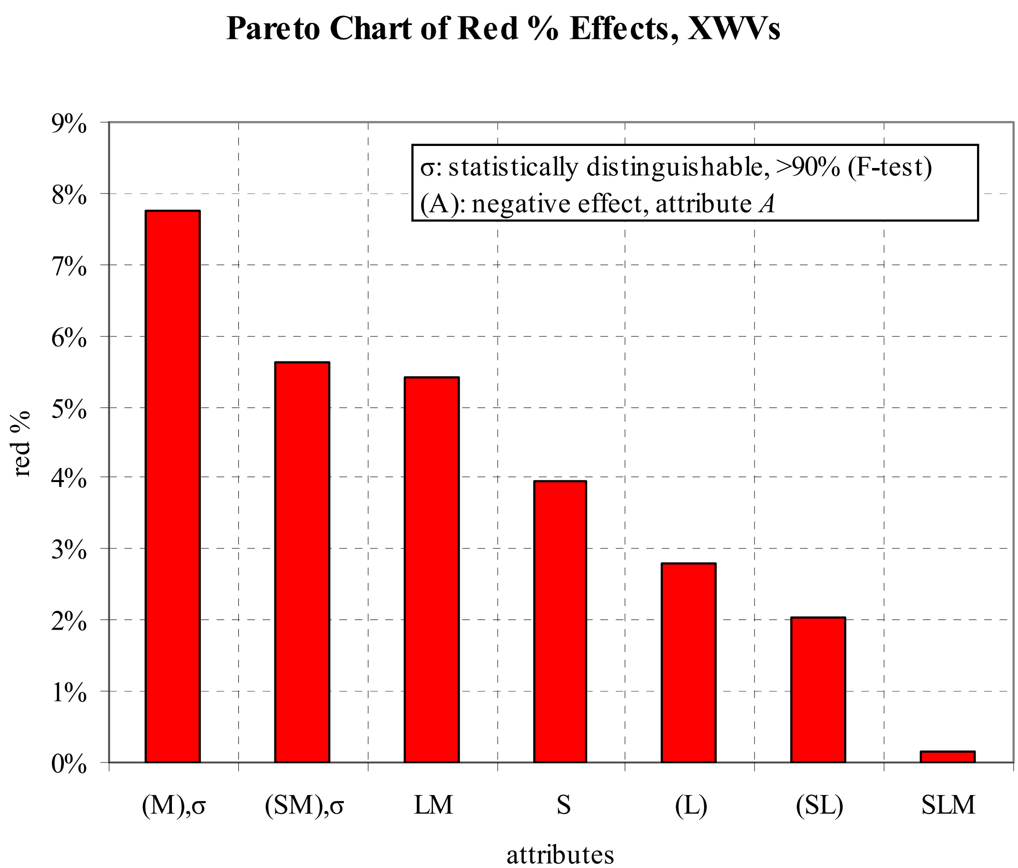
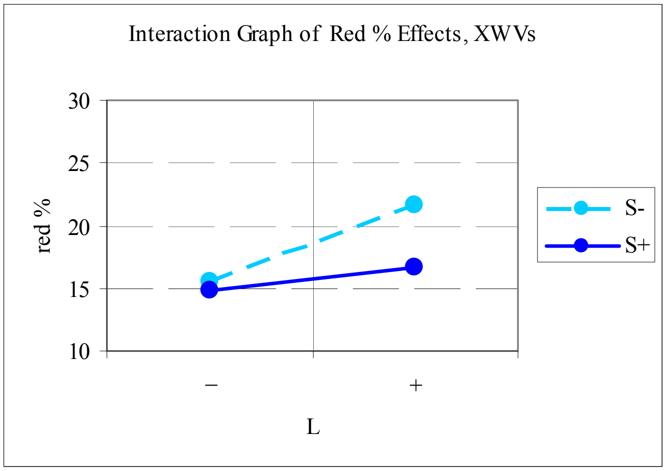
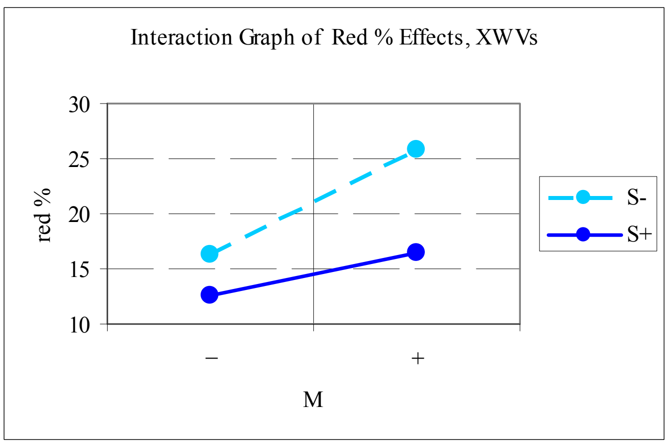


Figure 94: Pareto chart of red % effects, XWVs.

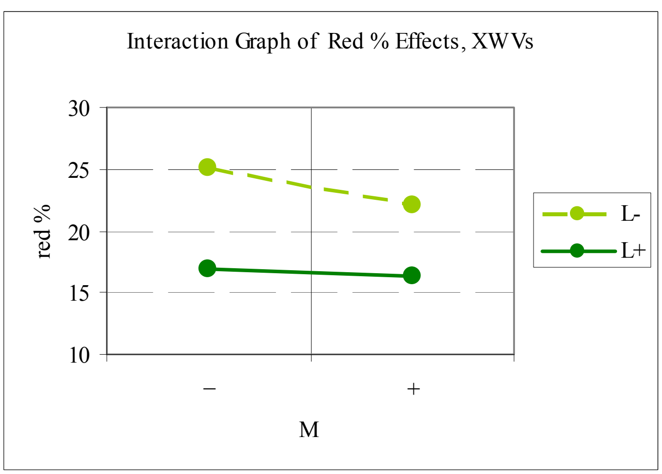
For the XWVs, mobility had the greatest effect on red %. For the same reasons stated for win %, the possession of enhanced mobility atop a commanding knowledge of the threat platform created detrimental effects for the enemy vehicle. And again, since the persistent attrition of threat health via an attack with machineguns would erode this metric regardless of a win, mobility was the most dominant attribute for XWV red %. The average decrease in red % (parenthetically annotated in Figure 68) from acceptable to enhanced levels of mobility was nearly 8%. There was also a positive interaction between survivability and mobility, presumably because the enhanced mobility platform was not substantially hampered by the heavier armor. Moreover, the extra protection afforded by enhanced survivability enabled the friendly system to survive in the game longer, providing more time to attrit the threat health and contribute to a decrease in red %.



The LS interaction is a type IVc, where both lethality and survivability have an effect as well as an interaction. The marginal for lethality (-8) is negative, but this is beneficial since we desire the red health to be low. The marginal for survivability (5) is positive, indicating a penalty for enhanced survivability, i.e., higher enemy health. The change in slope (2) indicates minimal interaction.



The MS interaction is a type IVc, where there is an effect from mobility and survivability as well as an interaction. The marginal for mobility (-10) is negative, indicating a beneficial trend (lower enemy health) with enhanced mobility. The marginal for survivability (5) is positive, indicating a penalty for higher survivability. The change in slope (2) is also minimal, indicating a low level of interaction.



The ML interaction is a type IVd, where there is an effect from lethality as well as an interaction. The marginals lethality (-8) and mobility (-10) are negative, indicating a benefit in enhanced lethality and mobility. The change in slope is high (8) indicating a strong interaction between mobility and lethality.

Figure 95: Interaction graphs of red % effects, XWVs.

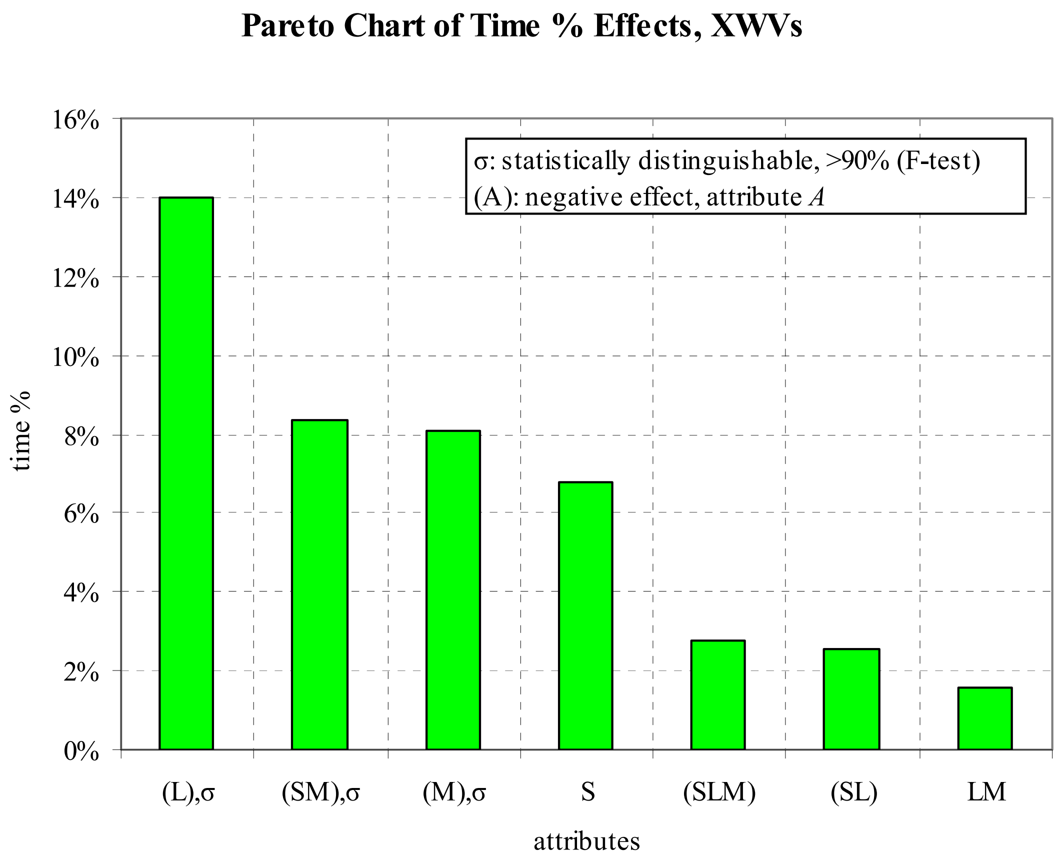
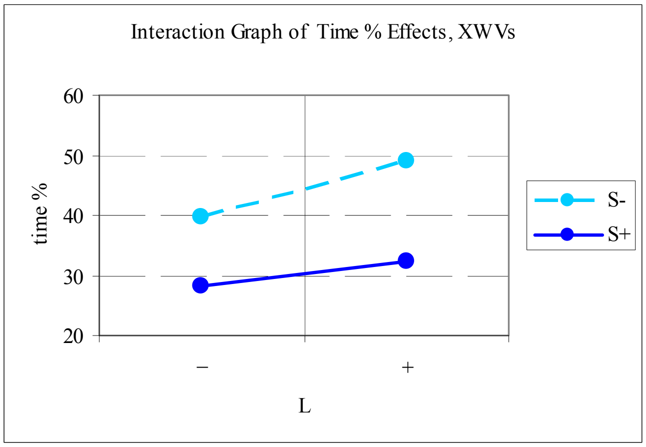
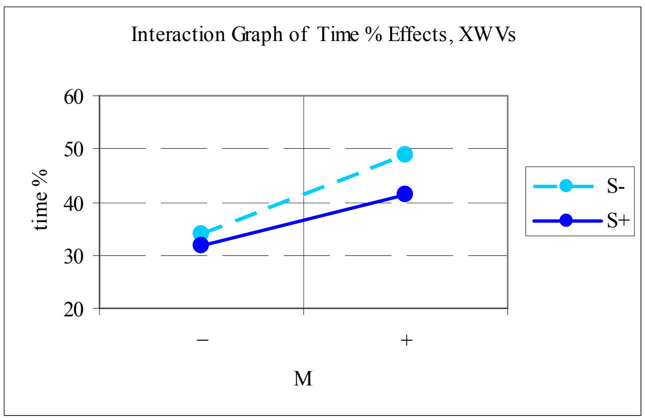


Figure 96: Pareto chart of time % effects, XWVs.

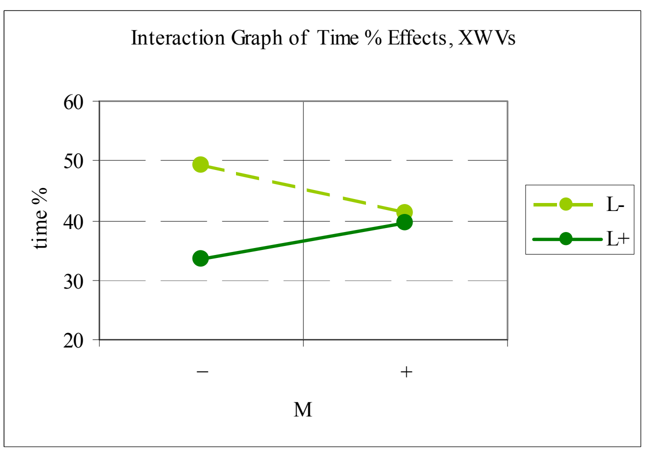
Surprisingly, lethality, not mobility, clearly had the greatest effect on time % for the XWVs. The average decrease in time % (parenthetically annotated in Figure 96) from acceptable to enhanced levels of lethality was over 14%. This is a nearly 37% reduction in mission time with respect to the average time % for the XWV variants. The interaction between survivability and mobility, as well as mobility alone were the next most distinguishable attributes with respect to reducing the time %. The average decrease in time % (parenthetically annotated in Figure 96) from low to high levels of lethality was over 8% for both. While an operator with the XWV variant could achieve commensurate levels of win %, blue %, and red % with a highly mobile platform, enhanced lethality was the attribute that could most definitively reduce the time to complete the mission. This was consistent across both XTV and XWV platforms. Additional armor was truly beneficial on an enhanced mobility, or to a less extent, an enhanced lethality platform; otherwise, it degraded performance noticeably.



The LS interaction is a type IVc, where lethality and survivability have an effect with an interaction. The marginal for lethality (-7) is negative, but this is beneficial since we desire the mission time to be low. The marginal for survivability (14) is positive, indicating a penalty for enhanced survivability, i.e., longer time. The small change in slope (5) indicates minimal interaction.



The MS interaction is a type IVc, where mobility and survivability have an effect as well as an interaction. The marginal for mobility (12) is positive, indicating greater time with enhanced mobility. The marginal for survivability (-5) is negative, indicating a reduction for enhanced survivability. The change in slope (6) indicates interaction between survivability and mobility.



The ML interaction is a type IVa, where there is an effect from as well as an interaction. The marginals for lethality (-9) and mobility (-1) are negative, indicating a benefit in enhanced lethality and mobility. The change in slope is high (14) indicating interaction between mobility and lethality.

Figure 97: Interaction graphs of time % effects, XWVs.

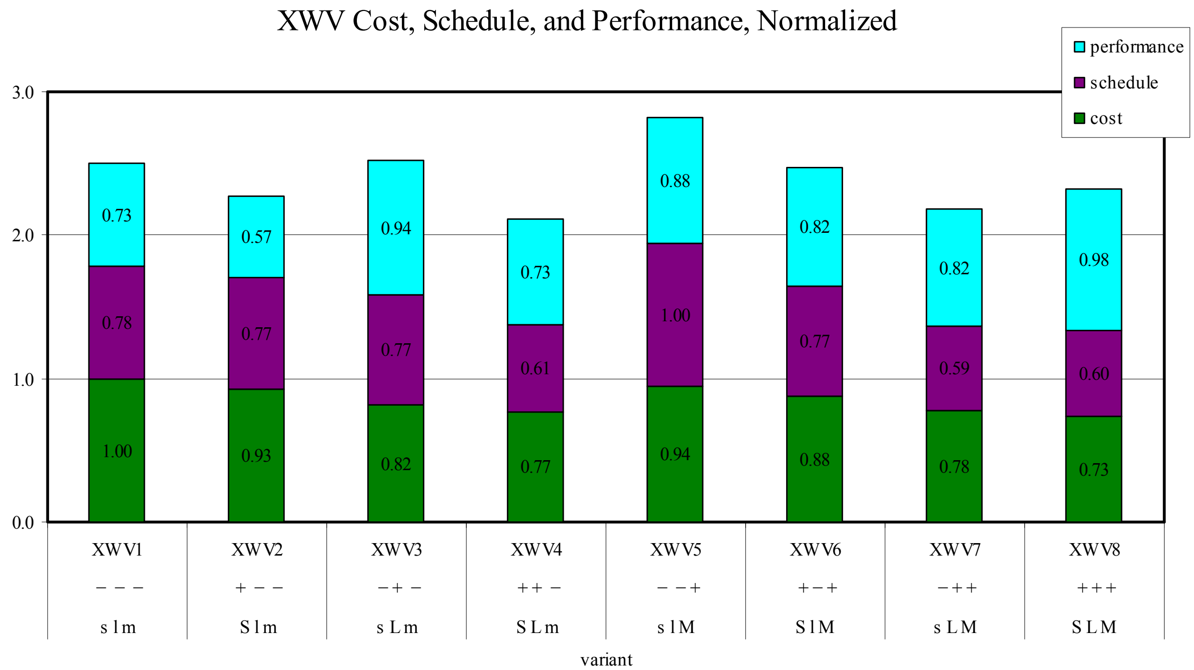


Figure 98: XWV cost, schedule, and performance (normalized). Performance is the sum of the normalized values for variant win %, blue %, red %, and time % divided by the number of metrics (4). Cost is the per vehicle cost normalized with respect to the variant with the lowest per vehicle cost. Schedule is the normalized schedule index with respect to the variant with the lowest schedule index.

In similar fashion to the analysis done for the XTVs, when analyzing Figure 98, the cheapest variant also had the second worst performance value, where only XWV2 performed worse. The best performing variant, XWV8, was the most expensive and had the worst schedule index. Again, the high performance of the apex variant came at a steep price and with considerable increase to the schedule index. While the two top performing candidates were fairly costly (XWV3 and XWV8), unlike the XTVs, mobility had a more dominant role in improving performance. Since this attribute was much cheaper to develop at an enhanced level, this created economical variants with performance approaching that of an enhanced lethality variant.

Table 45: Statistically Distinguishable (> 90% F-test) Attributes With Respect To XTV and XWV Performance Metrics

		XTV			XWV		
	Performance Metric	**$\sigma_{attribute(s)}$ >90% F-test**	**Figure**	**Page**	**$\sigma_{attribute(s)}$**	**Figure**	**Page**
a priori	**mass**	S, M, L	Figure 62	237	S, M, L	Figure 82	260
	cost	L, S, M	Figure 64	239	L, S, M	Figure 84	261
	volume	S	Figure 66	241	S	Figure 86	263
	schedule index	L	Figure 68	243	L	Figure 88	265
a posteriori	**win %**	L, M	Figure 70	245	none	Figure 90	267
	blue %	L	Figure 72	247	L, SL	Figure 92	270
	red %	none	Figure 74	249	M	Figure 94	273
	time %	L, M	Figure 76	251	L, M	Figure 96	276

The attributes affecting *a priori* performance metrics were very consistent between XTVs and XWVs. While survivability dominated the mass and volume of both tracked and wheeled vehicles, lethality was the greatest source of cost and increasing schedule index. The XTVs and XWVs shared all components and design choices across the two blocks of the experiment, and aside from the vehicle configuration and size, the components and subsystems were identical, e.g. XTV 8 and XWV 8. Therefore, it was expected that the attributes affecting these metrics would be consistent across blocks.

The results for the *a posteriori* performance metrics for XTVs and XWVs were similar, but more distinct across design configuration. Mobility took on a greater precedence for its contribution to XWV performance than it did for XTVs. In both XTVs and XWVs, lethality was the most significant attribute contributing toward improved time %. Unlike the other three *a posteriori* performance metrics, time % is insensitive to the means by which it is achieved. From this perspective, the value of lethality stood out for both XTVs and XWVs in enabling the mission to be completed as quickly as possible, thereby producing efficient and effective platforms.

With respect to attribute interactions, Table 46 serves as a cross-reference source for the type-classing of all principal attribute interactions for the *a priori* and *a posteriori* performance metrics. For example, if one was interested in the interactions associated with XTV mass, this table includes the graphs, type-classing of the interactions, and page number from the manuscript.

Table 46: Principal Attribute Interactions Classified and Cross Referenced for XTV and XWV Performance Metrics

		XTV				XWV			
Performance Metric		**Type**	**Effects**	**Figure**	**Page**	**Type**	**Effects**	**Figure**	**Page**
mass	LS	IIc	L, S	Figure 63	238	IIc	L, S	Figure 82	259
	MS	IIc	M, S	Figure 63	238	IIc	M, S	Figure 82	259
	ML	IIc	M, L	Figure 63	238	IIc	M, L	Figure 82	259
cost	LS	IIc	L, S	Figure 65	240	IIc	L, S	Figure 85	262
	MS	IIc	M, S	Figure 65	240	IIc	M, S	Figure 85	262
	ML	IIc	M, L	Figure 65	240	IIc	M, L	Figure 85	262
volume	LS	IIa	S	Figure 67	242	IIa	S	Figure 87	264
	MS	IIa	S	Figure 67	242	IIa	S	Figure 87	264
	ML	I	none	Figure 67	242	I	none	Figure 87	264
schedule index	LS	IVc	L, S, LS	Figure 69	244	IIc	L, S	Figure 89	267
	MS	IVb	S, MS	Figure 69	244	IIa	S	Figure 89	267
	ML	IVa	M, ML	Figure 69	244	IIb	L, ML	Figure 89	267
win %	LS	IVc	L, S, LS	Figure 71	246	IVc	L, S, LS	Figure 91	269
	MS	IIc	M, S	Figure 71	246	IVc	M, S, MS	Figure 91	269
	ML	IVd	M, L, ML	Figure 71	246	IVd	M, L, ML	Figure 91	269
blue %	LS	IVb	L, LS	Figure 73	248	IVa	S, LS	Figure 93	272
	MS	IVa	S, MS	Figure 73	248	IVc	M, S, MS	Figure 93	272
	ML	IVa	L, LM	Figure 73	248	IVa	L, LM	Figure 93	272
red %	LS	IVc	L, S, LS	Figure 75	250	IVc	L, S, LS	Figure 95	275
	MS	IIc	S, M	Figure 75	250	IVc	M, S, MS	Figure 95	275
	ML	IVd	M, L, ML	Figure 75	250	IVd	M, L, ML	Figure 95	275
time %	LS	IIb	L	Figure 77	253	IVc	L, S, LS	Figure 97	278
	MS	IVb	M, MS	Figure 77	253	IVc	M, S, MS	Figure 97	278
	ML	IIc	L, S	Figure 77	253	IVa	M, ML	Figure 97	278

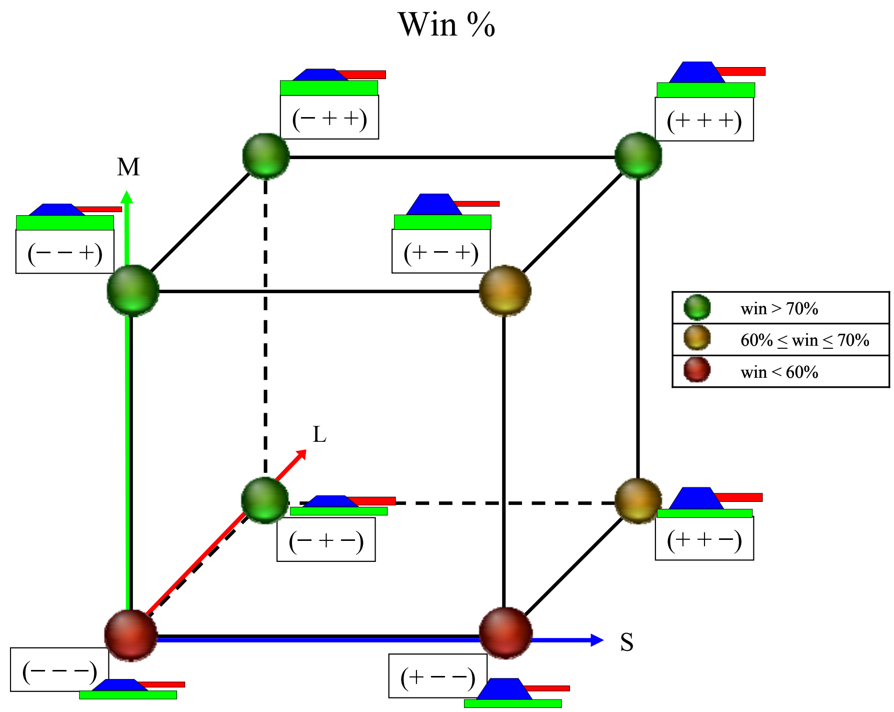


Figure 99: Average variant win record (XTV and XWV) in a survivability, lethality, and mobility domain. An XTV and XWV variant coincident at a point share the same relative levels of survivability, lethality, and mobility.

4.5 Relative Contributions and Interactions of Survivability, Lethality, and Mobility on Ground Combat Vehicle Performance

The results from the XTV and XWV JRATS missions (approximately 100 missions per variant) provided data for the four *a priori* performance metrics (mass, cost, volume, and schedule index) and the four *a posteriori* performance metrics (win %, blue %, red %, and time %). The following analysis is focused on the attribute effects and interactions contributing toward the observable trends and distinguishable contributions toward performance metric values when evaluating the difference between an acceptable and enhanced attribute level.

4.5.1 Analysis of Attribute Effects and Interactions On *A Priori* Performance Metrics of Mass, Cost, and Schedule Index

The DOE/ANOVA attribute effect analysis conducted on the three design metrics of mass, cost, and schedule index, was done with the absolute values produced from the JRATS design report. Having previously presented the results and observations on these values, more detailed analysis on the *a priori* performance metrics follows. A consolidated chart of the relative effects is first presented (Figure 100). In this chart, the attribute effects have been normalized with respect to the largest attribute effect. A red bar indicates a negative effect on the *a priori* metric of interest, and a green bar indicates a positive effect on the *a priori* metric of interest.

	Mass [kg]	Cost [$M]	Volume [m^3]	Schedule Index
XTV	S 180	L 1.5	S 8	L 29
	M 80	S 0.5	M 1	S 17
	L 40	M 0.4	L 1	M 12
XWV	S 170	L 1.5	S 5	L 43
	M 90	S 0.5	M 1	S 18
	L 30	M 0.4	L 1	M 5

Figure 100: Effects of principal attributes on *a priori* performance metrics for XTVs and XWVs. A red bar indicates a negative effect on the metric, and a green bar indicates a positive effect on the metric. The length of the bar has been scaled in length with respect to the greatest effect for that metric in the XTV or XWV block.

4.5.1.1 Mass

For both XTV and XWV variants, higher survivability had the greatest statistically distinguishable impact on vehicle mass (Figure 62 and Figure 82). The pursuit of higher survivability was achieved by upgrading the armor material from steel to depleted uranium. At high impact velocity, the denser armor material is better at retarding a penetrator's progress through the armor. High vehicle mass can also serve to diminish the effect of a blast by reducing global acceleration of the vehicle. While this denser material yielded a higher combat survivability index (CSI) rating, it produced an effect on mass more than twice that of the next ranking statistically distinguishable attribute, mobility. This finding is not surprising, as the armor commensurate with a well-protected combat vehicle comes at a penalty; in this case, high gross vehicle weight, can impede tactical movement as well as limit inter and intratheater transportability or operational and strategic mobility. All of the variants were of the same order in gross vehicle weight, with the difference in mass between the minimum and maximum XTV and XWV variants found to be 18% and 27% respectively. However, the average XTV was nearly 40% heavier then the average XWV, indicative of the penalty for possessing a higher CSI that comes with greater mass, heavier armor and a tracked platform.

From the vehicle mass breakdown analysis, it was clear that survivability assumed the largest fraction of mass penalty on the platform. Again, this was consistent with the results from Chapter 2 in which this attribute not only affected vehicle mass at the greatest rate, but also worked against the other principal attributes. The even-numbered XTV and XWV variants, which had high levels of survivability possessed, on average, 11% and 17% greater mass, respectively, than the odd-numbered XTVs and XWVs. While there were no statistically distinguishable interactions for mass, in practice, if the vehicle mobility performance were held constant with respect to the load requirement (gross vehicle weight), then one should expect an interaction between the attribute of survivability and mobility. The assumption of more weight for greater protection will lead to higher demand for capability associated with the attribute of mobility.

Mobility was the next ranking statistically distinguishable attribute on platform mass. As the virtual “bill payer” to transport the array of combat vehicle sub-systems, this was an expected result indicative of the large mass associated with complete powerplant and drivetrain sub-systems. Lethality ranked last in principal attribute relative effect on vehicle mass. This matches conventional systems that have collective masses of protective material and drivetrain components that dwarf the mass associated with the weapon system. For example, the Abrams tank weighs over 70,000 kg, but the entire cannon system to include the fire control system and a full complement of ammunition weighs less than 5,000 kg.

4.5.1.2 Cost

For both the XTV and XWV variants, higher lethality had the greatest statistically distinguishable impact on vehicle cost (Figure 64 and Figure 84). In fact, as can be seen in those figures, the effect from lethality on vehicle cost was nearly three times that of the next ranking attribute. The sophisticated nature and high technology related to modern combat systems remains a costly pursuit, particularly with the weaponry. The JRATS simulation placed a heavy premium on the high-performance lethality components like guided missiles and laser targeting and guidance system.

From the design reports, it also appeared that lethality caused the most distinguishable increase in per-unit cost. This was a relatively simple vehicle to design and virtually construct; however, analysis of this type on a more complex system would still be valuable to identify analogous critical pathways for the mass and cash associated with a system. When considering a program management tool like a Gannt chart, the critical pathway on a system is often the one identified as having the longest lead-time or the one with the greatest interconnectedness and relative reliance from other systems.

In the words of Norman Augustine, “agony is equal to ecstasy cubed”, a reference to prior work that illustrates the extreme increase in cost (agony) for incremental gains in performance (ecstasy). In these cases, every variant was relatively expensive and heavy. The cost ranges, between most and least expensive variants were of a similar scale with 28% for XTV and 27% for XWV candidates. Fighting vehicle performance comes at a high cost, but paramountly, failure to attain supreme performance over a foe consumes energy resources and potentially incurs the ultimate price, both to crew and to the nation which allocated resources in the first place. Survivability and mobility ranked behind lethality in terms of relative effect on vehicle cost. That said, enhanced protection technologies can be costly endeavors, and the physical challenges associated with defeating an insult on length and time scales an order of magnitude less than what is required to generate the insult are not trivial. As an attribute, one would expect mobility to have the lowest relative contribution to platform cost, since this is a relatively straightforward design effort that can leverage off commercial efforts.

4.5.1.3 Volume

The attribute that had the greatest effect on vehicle volume for the XTVs and XWVs was survivability (Figure 66 and Figure 86). This single attribute dominated the others with respect to the observed increase in vehicle volume at low and high levels. The enhanced armor associated with the highest combat survivability index caused a large increase, not only in vehicle mass, but also in vehicle volume. It should be noted that this relative improvement in protection was geared toward reducing vulnerability at the expense of being more susceptible. Statically, a vehicle with a greater presented area is more susceptible to attack, but may be more resistant to insult if the invulnerability is great enough. Dynamically, a vehicle that is sluggish, i.e., presents an easier target, could again be more susceptible to attack, but at the same time more resistant to insult if the invulnerability is great enough. More simply, big boxes are easier to hit than small boxes, and slow boxes are easier to hit than fast boxes.

The larger volumes occupied by the vehicles with greater protective levels of armor presented the threat platform with a larger target. More specifically, the greater survivability increased the length and width, or footprint of the platform, while the lethality increased the height of the platform. The greater lethality enabled by the guided missile system, which sat on a slightly elevated pedestal mount that increased the height of the vehicle by approximately 0.5 m. Navigating through the small city did not present any obstructions to vehicular movement, but in a more realistic environment the larger volume of the well-armored vehicles may have restricted movement for these variants in restricted terrain.

4.5.1.4 Schedule Index

The attribute that had the greatest effect on the schedule index on the XTVs and XWVs was lethality (Figure 68 and Figure 88). As previously discussed, this index was created from design report outputs in order to compile a nondimensional value depicting schedule considerations. An enhanced level of lethality brings with it increased cost and developmental effort. Therefore, in practice, it is probable that an advanced form of firepower could have the biggest impact on a schedule. As a group, the XTVs had slightly higher average schedule indices than the XWVs (172 versus 168). The pursuit of enhanced levels of survivability could also bring with it increased effect on the schedule index. In order to break the survivability paradox, i.e., that increased levels of protection through conventional means can make a system simultaneously less vulnerable to insult, but more susceptible to insult, a more mass and volumetrically efficient means of system protection is needed, say a surface that can visually cloak the vehicle with the background. Whether this pursuit is for an active, passive, or combination active/passive protection system, the effort to improve survivability will incur a large relative effect on the schedule index.

Again, in practice, there is considerable uncertainty associated with each of these values. Historically, cost overruns and schedule delays are more often the rule than the exception. In fact, cost and schedule often defer in priority to the absolute pursuit of supreme performance. The demonstrated DOE approach, with the inclusion of uncertainty related to attribute mass, cost, and schedule, could forecast programmatic impacts to cost, performance, and schedule through a sensitivity analysis and the related impact on program objectives. For example, since the effect on mass associated with lethality was quite small, even great uncertainty regarding the component weights dedicated to enabling this attribute would have a relatively low net effect on the gross vehicle weight. However, since survivability dominated the mass of the vehicle, even small uncertainty related to the protective components comprising the platform could potentially have a greater mass penalty on the system.

4.5.2 Analysis of Attribute Effects and Interactions On *A Posteriori* Performance Metrics of Win %, Blue %, Red %, and Time %

The attribute weighting results from Chapter 3 indicated that survivability held greatest precedence with survey respondents. The subjective metric crosswalk exercises done in Chapter 2 qualitatively demonstrated that the pursuit of greater levels of survivability compete with the attributes of lethality and mobility, since the mass associated with conventional armor protection can reduce the ability to maneuver or fire and move on the enemy from a position of advantage. Going into these exercises, it was somewhat expected that for all performance metrics, variant performance would begin at some arbitrarily low value for the minus-minus-minus (acceptable survivability, lethality, and mobility) vehicle, then slowly increase in efficacy until peak performance was observed for the plus-plus-plus (enhanced survivability, lethality, and mobility) vehicle. While this trend was generally true for both the XTVs and XWVs, some interesting patterns were observed, as well as some consistently dominant attributes with respect to the performance metrics of win %, blue %, red %, and time %.

A consolidated chart of the relative effects is first presented (Figure 101). In this chart, the attribute effects have been normalized with respect to the largest attribute effect. A red bar indicates a negative effect on the *a posteriori* metric of interest, and a green bar indicates a positive effect on the *a posteriori* metric of interest.

	Win % [%]	Blue % [%]	Red % [%]	Time % [%]
XTV	**L** 26 **M** 19 **S** 10	**L** 9 **S** 2 **M** 1	**L** 15 **M** 13 **S** 10	**L** 19 **M** 12 **S** 1
XWV	**M** 14 **L** 8 **S** 7	**L** 8 **S** 2 **M** 1	**M** 8 **S** 4 **L** 3	**L** 14 **M** 8 **S** 7

Figure 101: Effects of principal attributes on *a posteriori* performance metrics for XTVs and XWVs. A red bar indicates a negative effect on the metric, and a green bar indicates a positive effect on the metric. The length of the bar has been scaled in length with respect to the greatest effect for that metric in the XTV or XWV block.

4.5.2.1 Win %

For both XTVs and XWVs, lethality was the dominant attribute that contributed to the greatest increase in win % (Figure 70 and Figure 90). The advanced weaponry afforded to the variants with high levels of lethality demonstrated an increased ability to engage and destroy the threat vehicle in the JRATS simulation. Afforded to the operators with the addition of a potent guided missile system, the increased standoff and greater probability of kill that accompanied greater lethality improved variant win % markedly. The seek and destroy mission was most successfully pursued with a dominant source of firepower. As a group, the XWVs had nearly a 10% greater win % average than the XTVs at 72% to 60% respectively. Since the XWV block followed the XTV block, some fraction of the advantage may be credited to the experience gained from nearly 3 hours of simulation training and XTV missions. Additionally, all operators possessed driver's licenses, but notably none had ever driven a tracked vehicle prior to the exercise. While both the XTV and XWV variant peak win % came from the superlative design (+++ or XTV8 and XWV8), these variants only slightly edged out win % greater than lighter, cheaper variants that had high levels of lethality (Figure 59 and Figure 79). The greater lethality allowed the user to engage and destroy the threat platform in 2 decisive shots, while the lower lethality required a more concerted effort to continually engage the threat platform until the health rating had been attritted to zero.

4.5.2.2 Blue %

In similar fashion to the observations for win %, the XTV and XWV blue % performance metric was dominated by the effects of lethality (Figure 72 and Figure 92). Since the engagement scenario was evenly sided and conventional, the best protection appeared to be afforded by simply removing the threat from the battlefield altogether. This elimination was most heavily influenced by the possession of advanced levels of weaponry, but also enhanced mobility. In other words, in this notional and conventional fight in an urban environment, the best defense was offense. If the threat could be defeated prior to insulting the friendly platform, this gave the greatest protective benefit to the metric of blue %. Denying the threat an opportunity to engage the friendly vehicle had the most substantial effect on increasing blue % than in simply armoring the platform.

Survivability had a slight negative effect on blue % for both the XTV and XWV variants. The extra armor, while increasing the combat survivability index of the variant, made it a larger, slower and generally less nimble target. Mobility had a slight positive effect on blue % for both the XTV and XWV. The advanced level of movement afforded by the larger powerplant not only aided in maneuver, but reduced the susceptibility of the friendly platform by making it a more challenging target to hit.

4.5.2.3 Red %

For the XTVs, red % was most influenced by lethality (Figure 74), while for the XWVs, red % was most influenced by mobility (Figure 94). As a group, the XWVs induced more damage to the threat vehicles than the XTVs on an order similar to the advantage observed in the difference between win %. The XWV block of missions occurred after the XTV block, and at this point the operators had a commanding knowledge of the simulation scenario, as well as the threat vehicle search patterns. The possession of enhanced mobility enabled the operator to place a sustained rate of machine gun fire onto the threat platform, thereby reducing the threat health regardless of whether the mission ended with a win or not.

4.5.2.4 Time %

For both XTVs and XWVs, lethality was the dominant attribute for improving time % (Figure 76 and Figure 96), with the XTVs also being heavily influenced by mobility. Unlike the other *a posteriori* metrics, time % was singularly the only metric that could be measured irrespective of tactic or technique. For example, two radically different fighting styles employed on two unique variants may have produced similar values for performance with respect to win %, blue %, and red %, but the value for time % would serve as an independent measure of how quickly the mission was run regardless of tactic or technique.

The XWVs, possessing an already higher level of inherent mobility, did not observe the same commensurate benefit of higher mobility. As a class of vehicles, the

XWVs were markedly faster at completing the mission, enjoying more than a 20% advantage (lower value) in time % over the XTVs (37% versus 59%). The XWVs themselves were faster, and since the simulation was topographically benign and without cross country movement or obstacles, the potential advantage of a tracked configuration possessed by the XTVs were not demonstrable in this scenario. Additionally, as with the other *a posteriori* performance metrics, the operators during the XWV block had virtually mastered the game, both from an environmental consideration and from an enemy perspective. At this point in the experiment, the operators could virtually anticipate the spawning location and search patterns of the threat, thereby reducing the time % remarkably. Considering lethality and mobility as the constitutive elements of maneuver warfare, the XTV and XWV blocks demonstrated that these two attributes, either employed uniquely or in combination, led to the greatest reduction in time %. As an *a posteriori* attribute, this was the most conclusive, since various tactics and techniques may have produced a comparable win %, blue %, or red %, but only a fast, decisive engagement could affect the *a posteriori* metric of time % (Figure 76 and Figure 96).

4.5.3 Effects of Survivability

As previously noted, survivability had the greatest impact on increasing XTV and XWV mass and volume. It was the second most dominant attribute with respect to increasing per vehicle cost. The weight associated with the armor dominated the vehicle mass breakdown analysis and imposed a heavy (no pun intended) consequence on gross vehicle weight. The extra armor, assumed to be composed in a complex array similar to modern armor, had an even greater effect on variant volume. The higher protective levels increased the occupied volume by almost 50%. The deployability index was also hampered by the increased survivability associated with even-numbered XTV and XWV variants.

When analyzing the *a posteriori* metrics, while an upward trend was generally true from variant 1 to 8, i.e., that the performance for the first variant achieved some low level and gradually grew to some high level for the final variant, the surprising results were the downturns observed when system survivability increased at the exclusion of both enhanced lethality and mobility. As a sole factor, greater survivability had an observable negative effect on every *a posteriori* performance metric. With the exception of the apex vehicle designs (XTV8 and XWV8, both + + +, i.e., enhanced for survivability, lethality, and mobility), nearly every even-numbered candidate (enhanced survivability) had lower performance than its numerical predecessor. Remarkably, this was observed for both XTVs and XWVs. In other words, increasing survivability alone decreased performance, in some cases significantly.

Mission failures caused by time-outs were also associated with higher survivability. Of the 89 XTV mission time-out failures, 51 (58%) occurred on the more sluggish, even-numbered platforms. In addition, of the 11 XWV mission time-out failures, 8 (73%) were recorded on even-numbered variants. The greater mass, associated with more protection, hindered movement to the point that some operators simply could not maneuver the vehicle fast enough around the urban environment to engage the threat platform in the 15-minute mission time limit. Even if, at a platform level, this proved to be a winning tactic for crew survivability, this was a losing strategy for the employment of resources that could not complete the mission and extend the time crewmembers are placed at risk.

The only two variants that appeared to benefit from increased survivability were those that also had increased levels of lethality and mobility, i.e., XTV8 and XWV8. The high mobility was needed to adequately transport the extra mass associated with the greater armor protection. Statistically, there was no benefit on win % from higher survivability.

In Table 45, survivability had a negative effect and/or interaction on all global performance metrics. This was consistent with the results from Chapter 2 of this manuscript. Interestingly, this matched observed trends with the MRAP fielding particularly in OEF. From a mission success perspective, it was not a good technical approach to simply "armor-up" the platform. The steepest decline in performance from a numerical predecessor was from both XTV and XWV 1–2. Additionally, the highest learning curves for win % for both the XTV and XWV were on the second variant, i.e., the high survivability variant. For XTV2, there was a 7% learning curve from the first 5 missions to the final, and for XWV2, there was a 5% learning curve. In other words, the operators had to work harder to adapt at fighting a sluggish, albeit better protected (less vulnerable but more susceptible) variant. These findings warrant further analysis; they at least require some consideration as to how best attain high survivability by considering both vulnerability and susceptibility in fighting vehicle design.

For the XTVs and XWVs, survivability had a detrimental effect on reducing the enemy vehicle health. The lack of mobility imposed by a higher combat survivability index seemed to reduce the ability of the friendly platform to move to a point of advantage necessary to deploy a lethal payload. This means that, while the armor provided more passive protection to the friendly platform (i.e., reducing the vulnerability of the system), it could be considered more susceptible to attack since the friendly system had a reduced capacity to evade an attack. Perhaps due to their increased nominal masses, the tracked vehicles were not as significantly penalized with respect to time for carrying additional armor (high survivability). However, while not statistically distinguishable, the trend for survivability on wheeled platforms was to increase the mission time. This result matches practice, where most armored, well-protected vehicles are tracked. Wheeled chassis are not able to withstand the substantial weight and load dynamics associated with assuming a heavy armor shell.

It is worth restating that the JRATS notional search and destroy mission was an offensive, force-on-force, meeting engagement, absent many of the challenges and dangers of the COE, any of which could reinforce the benefit of higher survivability. In actual practice, it is quite possible that, while a less vulnerable platform may become mission incapable at a lower rate than a less armored variant, its crew may have a greater personnel survivability rate, given insult in a better-protected platform.

In other words, a vehicle may be less susceptible and therefore able to evade strikes in a smaller, more nimble platform, but any insult endured in the more vulnerable vehicle could prove to be the last. To use a naval analogy, low vulnerability versus low susceptibility could mean the difference between being dead in the water or being truly sunk. For Army fighting vehicles, survivability efforts are mainly focused on reducing vulnerability, whereas the Air Force and Navy have pursued contemporary systems with a concurrent focus on making systems less susceptible as well. In some extreme cases, the systems are exceedingly vulnerable, but were designed to be extraordinarily insusceptible due to stealth, speed, and range. This creates a composite survivability risk which is mitigated to an acceptable level by the overall system design. Regardless, in the context of this experiment, it appears that, while the greater armor afforded to the high survivability platforms reduced vulnerability, it made the platforms more susceptible to attack since these candidates were bigger and slower, hence actually less survivable from the perspective of possessing a platform with capacity to complete the prescribed mission. And as previously stated, if the vehicle target area is assumed as a rectangular prism encapsulating the vehicle, it is safe to assume that big boxes are easier to hit than small boxes, and slow boxes are easier to hit than fast boxes.

4.5.4 Effects of Lethality

Enhanced lethality for XTVs and XWVs created the greatest effect on both cost and schedule index. The achievement of superlative firepower came at the literal expense of advanced weaponry that was costly to develop and procure in the JRATS environment. However, this cost, when balanced with the apparent advantages in simulated combat performance, i.e., win %, blue %, red %, and time %. Additionally, of the three principal attributes, lethality had the smallest impact on vehicle mass, making advanced performance conducive with inter and intratheater mobility, as well as placing minimal demand on tactical mobility.

When analyzing the effect of principal attributes on the metric related to mission success, for both XTV and XWV variants, lethality was the dominant attribute most conducive with win %, blue % (via destroying the insult-producing threat), and reducing time %. The increased firepower associated with the high level of lethality substantially increased the ability of the platform to dominate the threat vehicle. Considering the simplicity of the engagement and the terrain associated with the JRATS simulation environment, the dominance of lethality among attributes and interactions may not be that surprising, since engaging and removing the threat from the battlefield was a sure-fire way to complete the mission efficiently, both for reducing time and protecting the friendly platform.

When analyzing the performance metric of blue %, it appeared from the results that the best defense in the combat simulation was offense both in terms of lethality and mobility (Figure 72 and Figure 92). For both the XTV and XWV variants, lethality had the greatest positive effect on residual platform health. Since the simulation only dealt with a single threat platform, the removal of enemy vehicle, enabled by greater lethality, made the entire simulation largely permissive and safe. Additionally, there was no IED threat in the simulation. With the inclusion of multiple threat vectors and a persistent IED presence in a simulation, the results could have more favored survivability as the dominant attribute contributing to blue health. However, in the context of this exercise, lethality not only served as the most potent attribute for mission success, it also had the greatest positive impact on preserving system health, measured as blue %.

As with the win % analysis, lethality was again the most dominant attribute for both reducing the time % for XTVs and XWVs (Figure 76 and Figure 96). The higher lethality ended the fight quicker, providing nearly double the effect on residual mission time than the next ranking attribute. Decisively engaging the enemy, preferable on the first meeting engagement, was apparently the best source of protection for the friendly platform, especially when done at a stand-off range that was not conducive with the threat vehicle being able to engage.

The benefit of advanced lethality was contained to the single vehicle representing friendly forces. However, with multiple systems fighting together, the benefit of advanced lethality could benefit neighboring platforms in an extrinsic fashion. In other words, the protective value of destroying threats on the battlefield can be shared. This is a capability only offered by lethality, since survivability and mobility are considered intrinsic attributes in that, except for hypothetical situations, the protection and movement generated by a platform is largely restricted to that single system.

4.5.5 Effects of Mobility

As the constitutive partner to lethality in ground maneuver warfare, mobility was the second ranking attribute in nearly every *a posteriori* metric for both XTV and XWV variants. Where lethality reigned supreme, mobility was the attribute secondary, albeit not always at a level necessary to satisfy the test for statistical significance. Mobility ranked second to lethality for XTV win %, red %, and time %. For XWVs, mobility was the top ranking attribute for win % and red %. For XWV time %, mobility ranked third in measurable effects. This lower ranking could be explained by how, even at low levels of mobility, the terrain favored the wheeled platforms and diminished the apparent advantage of additional capacity with this attribute.

More importantly, greater mobility contributed in a positive fashion toward every *a posteriori* performance metric. The high mobility XTV and XWV variants enjoyed a nearly 10% reduction in time %. The greater top speed and acceleration afforded by the high output powerplant allowed the operators to navigate around the city faster and find and subsequently engage the threat platform quicker. In this regard, mobility created positive operational effects on the order of enhanced lethality. The freedom to move about the battlefield at a greater rate generated beneficial effects similar to lethality.

4.5.6 Survivability, Lethality, and Mobility Interactions

Statistically distinguishable interactions among attributes were not observed in the DOE results from either the wheeled or tracked JRATS variants. The interaction of lethality and mobility, depicted as "LM" on the Pareto chart for win effect, did appear third for tracked vehicles and fourth for wheeled vehicles, but again not at a level commensurate with 90% confidence.

The author observed that ROTC mission operators used the enhanced performance of vehicle attributes to suit the mission. For example, an operator wielding a candidate platform with greater lethality (missiles) engaged at longer range and with greater precision in offensive pursuit of the threat platform. However, an operator possessing a vehicle with greater mobility adopted a more aggressive style of maneuver that capitalized on the faster acceleration and helped not only evade threat fire, but also enabled movement of the platform to a position of advantage. In other words, the operators fought the best they could with the platform they had. The operators adopted an offensive fighting style that best suited the variant; this may have muted the appearance of statistically distinguishable interactions between attributes than if a more prescriptive or automated fight plan was established.

In this respect, the singular and coupled effects of lethality and mobility observed in this experiment with regard to the global performance metrics may represent a quantifiable correlation of the ubiquitous military term called maneuver. High lethality universally led to better performance, and only when mobility was hindered by high survivability, did it not contribute to better performance results. Finally, and unlike the negative interaction of survivability, was the observation that lethality and mobility contributed in a complementary fashion to higher performance on the interaction charts. Absent from this observation was a more definitive value for the interaction of lethality and mobility on the charts of attribute effects.

This also echoes a similar conclusion made by Ogorkiewicz regarding vehicle design after World War II which:

> followed from the general acceptance of the fact that their effectiveness depends, above all else, on their gun-power and provides a contrast with the days when the

designers of the "infantry" tanks were preoccupied with armour protection and when the "cavalry" tanks were characterized by undergunned mobility.[189]

The interaction of these two attributes, while observable, was not statistically distinguishable. As single attributes, lethality and mobility (in that order) had the greatest positive impact on mission success, but the coupled effect was not statistically distinguishable. Interestingly, for both the wheeled and tracked vehicles, increased survivability had a negative effect on mission success. In the JRATS simulation, the presence of armor without increased means to move (mobility) or fight (lethality) contributed negatively toward the vehicle success rate.

4.5.7 Wheels Versus Tracks

In the combat vehicle design arena, the debate of "wheels versus tracks" ranks high on an arbitrary scale of combat vehicle design consideration contentiousness. The deliberations surrounding this basic vehicle architectural decision go back decades, and were hot topics during the selection of the Stryker, as well as the design phases of the Future Combat Systems (FCS) program. Since the JRATS environment was a very simple area to maneuver, with no incline or obstacles, only hard improved roads, and no cross country movement or major terrain features, the simulation did not reveal the superiority of tracked platforms on those terrains. The nominal win record for the eight wheeled vehicles was 72%, while the family of tracked vehicles averaged 60%. Additionally, less than 2% of wheeled missions were time-out failures (11 of 735), but almost 11% (89 of 825) of the tracked vehicle missions were of this type of failure. The tracked vehicles did produce slower mobility performance specifications, particularly in acceleration.

[189] Ogorkiewicz, *Design and Development of Fighting Vehicles*, 42. This quote appears in the beginning of his chapter on tank design and development since 1942.

From a resource management perspective, the tracked vehicles could be considered better since a time-out mission loss is a failure mode altogether distinct from a mission loss via enemy insult. No commander wants an unsuccessful mission, but a crew that fails to destroy a time-sensitive target by a prescribed point still lives to fight another day. Possible explanations as to why the operators performed slightly better on the wheeled chassis include the benefit of having conducted 800+ missions on tracked platforms prior to the wheeled variants. Previous Army studies:

> unanimously concluded that a tracked configuration is an optimal solution for tactical, high-mobility roles (off-road usage greater than 60 percent), gross vehicle weights in excess of 20 tons, and missions requiring unrestricted terrain movement, continuous all-weather operations, smaller silhouettes/dimensional envelopes, and greater survivability. [190]

International studies on this contentious topic produced similar results, adding depth to the discussion, by also evaluating the advantage in lethality provided by tracked vehicles.[191] Tracked vehicles typically provide a more stable weapon platform to fire from, yielding higher rates for probability of hit. In light of the actual benefits of tracked combat vehicles, the simulation results showed an advantage in wheeled candidates. Finally, it is also possible that the operators may have still been learning the subtle intricacies of maneuvering a tracked vehicle in the tight proximity of an urban environment.

4.5.8 Human Factors Considerations

Lastly, with regard to learning and variant distinction was an assessment of the correlation between gaming experience and performance. There was a moderate, but not insignificant correlation (0.5) between self-reported weekly gaming activity and average

[190] Paul Hornback, "The Wheel Versus Track Dilema" *Armor Magazine* (March-April 1998) 33-35.
[191] Jurgen Erbe, "Wheels or Tracks?" *Military Technology* (July 1994) 10-17.

performance. And aside from the best ranked and two worst ranked ROTC cadets, there was variation in rankings among individuals from the tracked series to wheeled series with an average change in performance rank of 3. Modern mounted warfare can trace its lineage back to medieval knights and the horse-mounted cavalry. In the spirit of this military ancestry, to use a contextual cavalry analogy, in this small sample it appeared there was one “bell sharp” (best performer), 11 “troopers” (moderate performers), and two “shavetails” (low performers).[192] This assessment is based on rankings where the individual performance on a platform was compared to the group average performance on those same candidates.

The operators learned the JRATS system very quickly, progressing through the TWV and TTV training session in nearly half the time allotted. Additionally, the group discussions during the training session disseminated a collective batch of tactics, techniques, and procedures that benefited all the operators. Having spent nearly three hours in the training and XTV missions prior to the second block consisting of XWV missions, the results were somewhat muted by the fact that the operators had figured out how to deftly “game the system” via near absolute dominance of the threat platform. Additionally, the operators began to sense or recognize the gradient associated with the variant numbering convention. This seemed to only improve the performance of the operators and is realistic in that a mounted warrior would want to know both the capabilities and limitations of the combat platform.

[192] Emmett M. Essin, *Shavetails and Bell Sharps: The History of the U.S. Army Mule* (Nebraska: First Bison Books, 1997), 96-97. Before the quartermaster presented a new mule to the train, the tail was shorn to provide an easily recognizable symbol to the train master. As the tail grew out, and the mule learned to take its place autonomously at the sound of the bell, this distinguishing physical feature would disappear. The same methodology was used for horse mounted cavalry troopers. Upon initial assignment of horse and tackle, the tail was shaved to enable the veterans with a quick way of identifying the at-risk, inexperienced soldiers. Again, as the tail grew, the trooper was simultaneously gaining experience. The term endures today in modern cavalry units, where newly assigned troopers are often referred to as “shavetails”.

4.6 Lessons Learned

- Lethality appeared to be the dominant principal attribute for simulated combat vehicle performance, showing a distinguishable, positive benefit for every *a posteriori* performance metric, i.e., increasing win % and blue % while reducing red % time %. Mobility had a similar positive effect on every *a posteriori* performance metric.
- Greater survivability had an observable negative effect on every performance metric, except the "triple plus" (enhanced survivability, lethality, and mobility). Survivability was also the greatest source of mass for the platforms, both from the DOE/ANOVA data and the vehicle mass breakout study. The simple mission environment, free of IED threats, could have favored a more protected platform.
- No statistically distinguishable attribute interactions were observed, but lethality and mobility clearly complemented each other in that both had commensurate levels of positive effect on performance. This matched the doctrinal definition of maneuver, or the use of fire and movement to dominate the enemy.
- The mission operators performed slightly better on the wheeled variants versus the tracked candidates. This could have been due to increased proficiency (wheeled block followed tracked block of experiment) and general familiarity with wheeled vehicles.
- The operators controlling the platform during the offensive mission modified their tactics to capitalize on the advantages afforded by the platform. This reduced the possible display of attribute interactions or coupling of effects, but also reinforced the value of considering human factor interaction with system performance. In other words, it may be difficult to imagine how an operator will employ an advanced capability, therefore the value of including operators in an exploratory fashion such as this can demonstrate novel use not previously considered.

4.7 Conclusions

In conclusion, this chapter demonstrated that it may be viable to prototypically design simulated combat platforms using a DOE construct in order to calculate statistically distinguishable correlations between the attributes of survivability, lethality, and mobility with respect to performance metrics. The simulation and modeling effort, which included human subject mission operators, was insightful particularly with respect to the employment of the weapon systems in relation to the computer-controlled threat platform. From this basic simulation exercise, lethality was the most dominant attribute, serving as a statistically distinguishable source of greatest effect with respect to the performance metrics. This attribute was also reinforced subjectively by its maneuver counterpart, mobility.

Somewhat disappointing was an absence of statistically distinguishable interactions, particularly an observance of a lethality–mobility interaction toward a performance metric. As individual attributes, lethality and mobility were the dominant sources for increased platform efficacy. Together, they had a marginal, but statistically insignificant, effect. Unique fighting styles for each type of platform may have masked observable interactions.

Perhaps paradoxically, survivability was observed to have a negative effect on nearly every performance metric, *even* friendly vehicle health. Many observations were well below statistical significance, i.e., in the noise of the problem, but this was a consistent observation across XTVs and XWVs. This is somewhat counterintuitive, since conventional wisdom is to protect the platform at all costs. Perhaps the simplistic nature of the simulation (i.e., single threat vehicle with no IEDs) was unable to completely portray the COE, an environment defined by a lack of definition and a persistently evolving unknown threat. That said, a more sophisticated simulation may reinforce (or further refute) the value of this attribute in performance metrics, but as it stands, with respect to the data collected from the 1,600 missions run in support of this DOE construct, lethality was the clear winner.

The value and significance of an approach such as this is that, in the absence of an empirical model which can capture the net platform effect from tuning attribute thresholds, the analysis of the results can demonstrate to the decision maker what principal attributes (and related secondary traits and tertiary metrics) are contributing to or in some cases driving *a priori* or *a posteriori* performance metrics. With the additional inclusion of uncertainty, the results provided could be elevated even higher, given that virtually any developmental pursuit as ambitious as the undertaking of designing and testing a ground combat system involves large amounts of risk and uncertainty. Without a contextual understanding for these impacts, in this case provided by a prototyping software tool, the pursuit of requirements related to metrics can contribute in an insignificant way, or worse yet, hinder performance while adding to the schedule and hence cost. Finally, as a program evolves over time, a method such as this could demonstrate to the decision maker which metrics, traits, and attribute is sacred ground, critical to mission performance. Likewise, those areas not demonstrated as contributing in a statistically distinguishable way toward performance goals could be relaxed in order to relieve programmatic pressures associated with cost, performance, and schedule.

The respondents surveyed in Chapter 3 deemed survivability as the most important attribute in combat vehicle design. In Chapter 2, the qualitative assessment of principal attributes, as well as the fielded ground combat vehicle principal attribute ranking analysis (Figure 24) indicated that the pursuit of enhanced survivability can impede the achievement of ground combat vehicle performance measures. Likewise, the achievement of superior strategic mobility, afforded by a compact, light vehicle, constrains the design and limits performance. In the set of variant platforms, XTV1 and XWV1 would have earned high marks for strategic mobility, yet their *a posteriori* performance was poor, besting only the enhance survivability platforms (XTV2 and XWV2). In essence, the collective contribution of combat vehicle survivability, lethality, and mobility, coalesce to yield a capable fighting platform. Within this group of attributes, the results from Chapter 4 indicated that lethality was the dominant attribute in achieving peak performance under a mission simulating offensive operations against a peer threat. In an effort to explore the ability to generate greater target effects in pursuit of higher lethality, the next chapter will explore the advanced weapon concepts related to both powder cannons and railguns.

Chapter 5: Advanced Weapon System Concepts—Conventional Cannonry Versus Electromagnetic Guns

> There are three stages of scientific discovery: first people deny it is true; then they deny it is important; finally, they credit the wrong person.
> —*Alexander Von Humboldt*

> Give them the third best to go with; the second best comes too late, the best never comes.
> —*Sir Robert Watson-Watt*

5.1 Introduction

A pair of combat platforms, namely a tank and an infantry fighting vehicle (IFV), each with protection capabilities representative of a future conventional threat, were established as challenging targets for an advanced weapon system design effort. In light of the results from Chapter 4, with lethality clearly being the dominant principal attribute for creating advantageous effects with performance metrics, the focus for this effort was to pursue enhanced levels of lethality in a two-pronged approach: one prong was to create an evolutionary improvement in lethality performance using conventional powder gun theory and concepts, while the other prong was to create a revolutionary improvement in lethality performance using railgun theory and concepts. A railgun is defined as a specific disruptive weapon technology within the general class of electromagnetic launch devices. While it appears that neither the advanced tank-caliber powder gun nor railgun concepts could be feasibly designed to defeat an advanced future tank threat from a mobile, tactical system, the railgun concept could theoretically be engineered to destroy advanced IFVs with the added benefit of developing and exploring a new range of performance opportunities possible when, perhaps in the future, projectiles are launched using electromagnetic forces instead of gas pressure generated from burning propellant.

5.2 Discussion

If the possession of dominant levels of lethality is the most important attribute a combat vehicle can have in the performance of major combat operations, then the objective of this chapter was to explore how theoretical weapon systems could be advanced in pursuit of greater lethality. In recognition of the most dangerous course of action ground forces are charged with conducting, the explicitly stated mission of the U.S. Army is to "fight and win our Nation's wars by providing prompt, sustained land dominance across the full range of military operations and spectrum of conflict in support of combatant commanders." For a ground combat vehicle, good strategic mobility yields prompt responsiveness. A design with high battlefield efficiency enables the operational level of war to sustain this combat power for greater duration. If, as the old military saying goes, "amateurs talk tactics, and experts talk logistics", then the most sophisticated analysis on fighting vehicle design should occur at the operational level of war. Deployed maneuver units place huge demands on the network of logistical support, so an efficient projection of combat power can yield large savings throughout.

At the tactical level, platform dominance is a strong function of capability overmatch, or the materiel performance advantage leveraged against the foe.[193] The overmatch is a function of a crew's ability to quickly, accurately, and efficiently generate target effects that impede or prevent the threat platform from generating an insult. Recognizing the value of Just War Theory, and the related principles that guide military development pursuits in a moral and ethical fashion, the truth remains that fighting vehicles are designed to enter the fray and fight.

[193] Stephen Biddle, "Victory Misunderstood: What the Gulf War Tells Us About the Future of Conflict" *International Security*, Vol. 21, No. 2 (Fall 1996). Biddle also argues that there is a strong interaction between technology and skill in producing a benefit.

The fact that a combat platform must be mobile and survivable is in accompaniment of its inherent lethality. As previously discussed, at the core of its functional capabilities, a ground combat system can simply be considered as a mobile and protected source of firepower. The lethality is derived from the ability to generate power and deliver energy on a designated target. The weapon energy is either absorbed into the target or passes through the armor as residual energy. The residual energy that perforates the armor can go on to damage proximal components (Figure 102). Perhaps then, it is not surprising that lethality was the most statistically significantly attribute in achieving performance objectives in the combat simulations conducted in the previous chapter. As previously observed and discussed, this attribute, dominated nearly every performance metric in a complementary fashion.

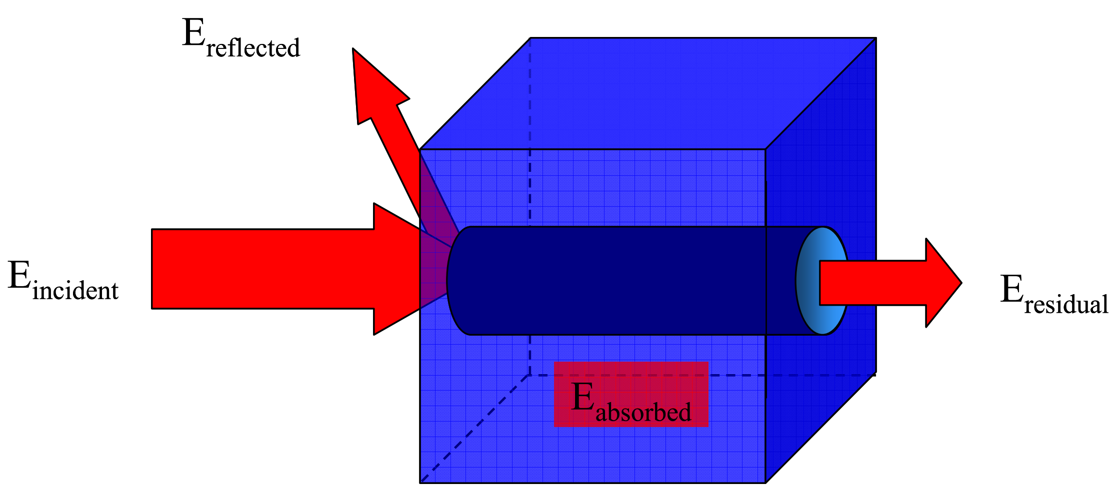


Figure 102: Notional target (blue cube) being insulted by a vector quantity of incident energy (red arrow) of an unspecified type. A fraction of this energy is reflected, some is absorbed into the target, and a portion passes through the target as residual energy.[194]

[194] LTG (R) Dutch Shoffner provided the original idea for this target-insult interaction graphic.

The scaling analysis done in Chapter 2 also illustrated the extreme challenges concerned with protecting against advanced lethality. The length and time scales associated with retarding an insult are approximately an order of magnitude less than in generating the insult. Using a tank cannon as an example, the insulting (delivering) system has approximately 5 m of cannon length and 5 ms of launch time to generate 10 MJ of kinetic energy. For a passive system, the insultee (receiving) system may have only 0.5 m of armor and less than 0.1 ms to mitigate the insult in order to protect the crew from injury and avoid catastrophic damage to the fighting platform. The engineering fields of both armor and cannons are notably mature, and even fractional improvements in performance requires long-term committed efforts to tease greater capability from what under previous conditions and design capabilities were considered optimized designs.

From an engineering perspective, an investment in higher lethality poses a considerable design challenge to the highly constrained recipient system. Stated alternatively, for a simple system the physical burden of defending against an advanced threat is higher than in generating it. It may be observed in nature that for similar physical reasons *we learn to throw before we learn to catch.* In harmony with the U.S. Army's strategic mission statement, a fighting vehicle must primarily dominate its opponent. An efficient design enables economical and persistent sustainment throughout operations. To provide a strategically prompt response, the system should have good measures for transportability. The classical notion of lethality connotes complete destruction of the threat system. However, when considering scalable or tunable consequences induced to a threat system, a spectrum of seven target effects (Figure 103) can be considered.

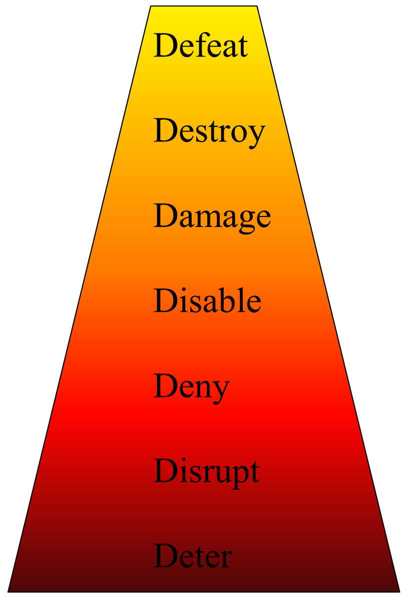


Figure 103: Spectrum of target effects ranging from deterrence to unqualified defeat.[195]

Among the principal attributes defined and explored, lethality is further distinguished from survivability and mobility in that lethality can be shared among friendly systems and deployed in support of adjacent elements. Multiple systems can use their lethality to converge on a single target (massing of fires), and a dominant lethal asset can be used to directly support a friendly element, e.g., from a support by fire or attack by fire position. Therefore, greater lethality, unlike survivability and mobility, can benefit systems not in direct possession of the weapon system. Prior to virtually designing a powder gun and railgun system with the explicit objective of destroying an advanced set of notional threat platforms, it is instructive to investigate the relative requirements for performance overmatch through the lens of a series of warfare modeling differential equations known as the Lanchester Laws of Combat.

[195] The source for this concept of scalable weapon effects can be credited to Mr. Scott McPheeters, U.S. Army Acquisition Project Manager, Directed Energy Applications Office, Redstone Arsenal, Alabama. This concept was originally presented at the Electric Fires Symposium, hosted by the U.S. Army Fires Center of Excellence, Fort Sill, Oklahoma in August, 2010.

5.3 Lanchester Laws of Combat

Developed during World War I, the equations describing the Lanchester Laws of Combat occupy a prominent place in the study of warfare.[196] The two most significant contributions from this work—the direct fire square law and the indirect fire linear law—remain at the core of many contemporary Department of Defense combat simulation computer models. These elegant equations offer many strengths, including the ability to "shed light on the quantity versus quality debate" with "a simple paradigm for understanding the dynamics of combat."[197]

Originally developed for aerial combat, the Lanchester Laws were found to function well at mathematically describing conventional, homogeneous ground warfare engagements. Late in the 1960s, these laws were further developed to account for unconventional, asymmetrical, and heterogeneous warfare like the campaigns typifying counterinsurgency operations in the Vietnam War. Proponents of the Lanchester Laws appreciate its "virtue of simplicity: [since] it makes strong simplifying assumptions, which nevertheless are (at least sometimes) close to being realizable." [198] The models as well "bring out, through a subtle process, some stark conclusions" especially regarding the balance of quality or effectiveness and quantity or number of forces. [199]

[196] John W.R. Lepingwell, "The Laws of Combat? Lanchester Reexamined", *International Security, Vol. 12, No 1,* (Summer 1987) 89-134.
[197] Ibid.
[198] Niall MacKay, "Lanchester combat models" *Mathematics Today*, (June 2006).
[199] T. W. Lucas and J. E. McGunnigle, "When is model complexity too much? Illustrating the benefits of simple models with Hughes' salvo equations" *Naval Research Logistics* (2003) 197-217.

5.3.1 Lanchester Square Law for Direct Fire

When considering line-of-sight or direct fire engagements, the Lanchester square law is applicable. Simplifying assumptions include that weapon fire is distributed evenly over targets, all targets are visible and targetable, and the consequences of insult are determinable so fires are immediately shifted.

The basic square law equations are presented below as Equation 41and Equation 42. In these equations, R(t) is the size of the red (enemy) force at time t, r is the effectiveness of red's fire on blue forces, B(t) is the size of the blue (friendly) force at time t, and b is the effectiveness of blue's fire on red forces. Solving these two equations for the case of equally matched forces gives the square law equality condition (Equation 43). "This equation states that two forces are equal when the products of the square of their force levels and their effectiveness are equal."[200]

$$\frac{dB(t)}{dt} = -rR(t) \qquad \text{Equation 41}$$

$$\frac{dR(t)}{dt} = -bB(t) \qquad \text{Equation 42}$$

$$r\left[R(0)\right]^2 = b\left[B(0)\right]^2 \qquad \text{Equation 43}$$

$$\frac{dB(t)}{dR(t)} = \frac{rR(t)}{bB(t)} \qquad \text{Equation 44}$$

The significance is that the appropriate measure or scale of a force's military capability is the force level squared times its effectiveness.[201] For example, if a force level is doubled, its fighting strength is increased by a factor of four, while if its

[200] John W.R. Lepingwell, "The Laws of Combat? Lanchester Reexamined", *International Security, Vol. 12, No 1,* (Summer 1987) 96.
[201] Ibid.

effectiveness is doubled, the fighting strength simply doubles. By observing the differential causality ratio from Equation 44, the force attrition equations have been derived explicitly and are subsequently depicted in Equation 45 and Equation 46.

$$B(t) = B(0)\cosh\left(\sqrt{rb}t\right) - \sqrt{\frac{r}{b}}R(0)\sinh\left(\sqrt{rb}t\right) \qquad \text{Equation 45}$$

$$R(t) = R(0)\cosh\left(\sqrt{rb}t\right) - \sqrt{\frac{b}{r}}B(0)\sinh\left(\sqrt{rb}t\right) \qquad \text{Equation 46}$$

These equations have also been solved to get the time at which the loser's forces go to zero, where the loser is defined as the side, red or blue, possessing less combat strength at the outset, i.e., values for r, R(0), b, and B(0) in Equation 43 produce an inequality (Equation 47).

$$t_{\text{end}} = \frac{1}{\sqrt{rb}}\tanh^{-1}\left(\frac{B(0)}{R(0)}\sqrt{\frac{b}{r}}\right) \qquad \text{Equation 47}$$

The square law equations "depend upon the forces being sufficiently large that the discrete firing processes can be approximated by the continuous differential equation."[202] For conventional warfare involving U.S. ground forces engaged with a peer threat, it is likely that the threat will be a numerically superior force.[203] The significance of this observation, when considering the Lanchester square law, is that friendly forces must possess an inordinately high level of combat effectiveness with respect to the opposing

[202] John W.R. Lepingwell, "The Laws of Combat? Lanchester Reexamined", *International Security, Vol. 12, No 1,* (Summer 1987) 129.
[203] James Hackett, *The Military Balance 2010*, International Institute for Strategic Studies (London: Routledge, 2010). The United States ranks in the top ten in a list of countries by size of troops when accounting for active, reserve, and paramilitary forces. In the event of ground troop involvement against a peer threat, these operations would occur in an overseas contingency environment, meaning that forces would be deployed in some fraction of the total combat power available to the nation. On the included list of financial expenditures, the United States is the clear global leader.

force in order to generate a fighting strength predictive of success in the anticipated battle.

In other words, it is inadequate to possess marginal capability overmatch against a peer threat. To counter the squared numerical benefit of a relative troop strength differential, the friendly forces must possess factor levels of greater effectiveness. The notion of this balance of power revolves around the "quantity versus quality" debate best captured by Stalin when he reflectively stated that "quantity has a quality all its own." In Figure 104, the square law was used to simulate a meeting engagement of a friendly infantry brigade with 2,500 soldiers opposing a threat infantry division with 10,000 soldiers. After 72 hours of continuous fighting, the friendly forces have finally achieved numerical superiority, but the fighting effectiveness required to achieve this was nearly a factor of 20 times greater ($b = 0.09$ versus $r = 0.005$).

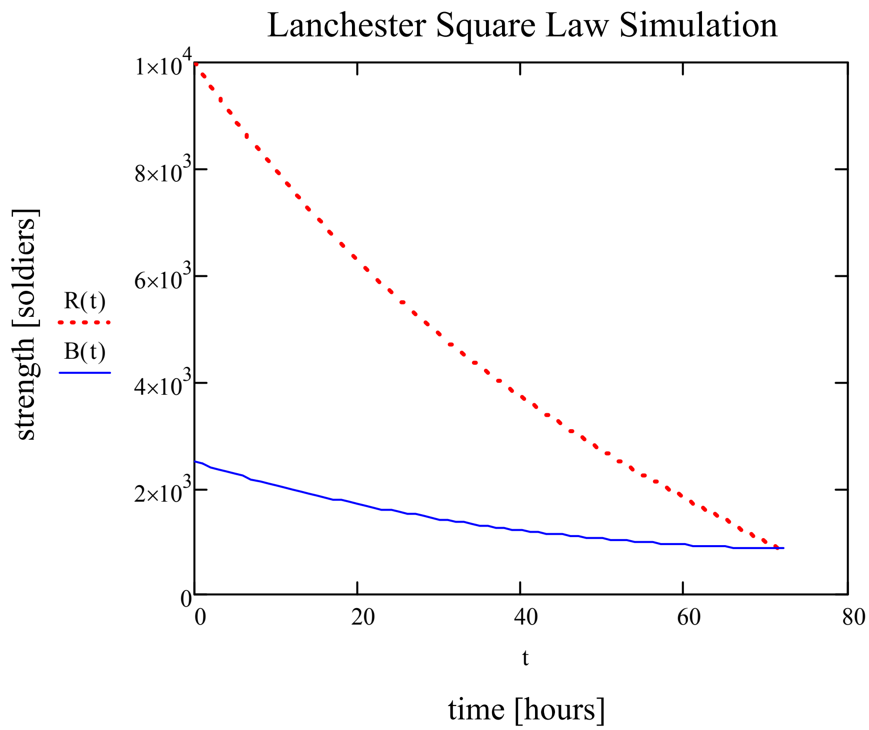


Figure 104: Lanchester square law simulation for a friendly (blue) force infantry brigade opposing a threat (red) force division, an approximately 1:4 numerical ratio of forces. The threat force began the battle with 10,000 soldiers, while the friendly force began with 2,500 soldiers.

Since their introduction in 1916, these equations have been further developed and utilized at much higher levels of complexity in order to account for heterogeneous forces, composite units, attrition, movement, and even morale. Even under all cases of additional complexity, the dominant elements remain as quantity and quality, or the size of converging forces and the effectiveness of those fighting units. For direct fire engagements, knowing how dominant the attribute of lethality was in creating successful fighting vehicles in the JRATS simulations, the Lanchester square law can demonstrate that if one expects to be numerically inferior to an opposing force, it is insufficient to simply possess a "safe" margin of superiority in effectiveness against a peer threat. Rather, the design goal should toward levels of performance approaching outright dominance in order to garner the combat strength necessary for a friendly force to attain mission success against a numerically superior foe.

5.3.2 Lanchester Linear Law for Indirect Fire

When considering non-line-of-sight or indirect fire engagements, the Lanchester linear law is applicable. Simplifying assumptions include that weapon fire is distributed evenly over an area and not specifically aimed at targets, firers do not have information on the effects of fire, and targets can potentially be fired upon after destruction.

The basic linear law equations are presented below as Equation 48 and Equation 49. In these equations, R(t) is the size of the red (enemy) force at time t, r is the effectiveness of red's fire on blue forces, B(t) is the size of the blue (friendly) force at time t, and b is the effectiveness of blue's fire on red forces. "If homogeneous forces with the same weapons and vulnerabilities on each side [are assumed]" then the linear law equality can be used (Equation 50). "The linear law differs from the square law in several important respects. First, it does not give any special advantage to force level. Second, concentration of forces has no effect on reducing the winner's total casualties."[204]

$$\frac{dB(t)}{dt} = -rR(t)B(t) \qquad \text{Equation 48}$$

$$\frac{dR(t)}{dt} = -bB(t)R(t) \qquad \text{Equation 49}$$

$$rR(0) = bB(0) \qquad \text{Equation 50}$$

$$\frac{dB(t)}{dR(t)} = \frac{r}{b} \qquad \text{Equation 51}$$

[204] John W.R. Lepingwell, "The Laws of Combat? Lanchester Reexamined", *International Security, Vol. 12, No 1,* (Summer 1987) 102.

These linear-law differential equations have also been explicitly solved as a function of time to generate attrition relationships for both blue and red forces (Equation 52 and Equation 53). As with the square law simulation, the blue force needs a significantly higher effectiveness, this time a factor of five greater than the red force, in order to generate numerical superiority during the 72-hour battle (Figure 105).

The described organized-chaos and fog-of-war present in modern combat in major combat operations appears to have qualities of both the linear and square law. While these laws and the accompanying examples are recognized to be highly idealized cases, they remain an integral part of combat simulation methodology.

Weapon developers working toward materiel solutions for an expeditionary force chartered to fight and win wars should strive for capability overmatch approaching order of magnitude greater effectiveness when compared against peer threat systems. For direct fire platforms, this means that metrics contributing to enhanced lethality should be expanded as far as possible in the operational envelope.

$$B(t) = B(0)\exp\left(-\left(rR(0)-bB(0)\right)t\right)\left[\frac{rR(0)-bB(0)}{rR(0)-bB(0)\exp\left(-\left(rR(0)-bB(0)\right)t\right)}\right]$$

Equation 52 (above)

$$R(t) = R(0)\left[\frac{rR(0)-bB(0)}{rR(0)-bB(0)\exp\left(-\left(rR(0)-bB(0)\right)t\right)}\right]$$

Equation 53 (above)

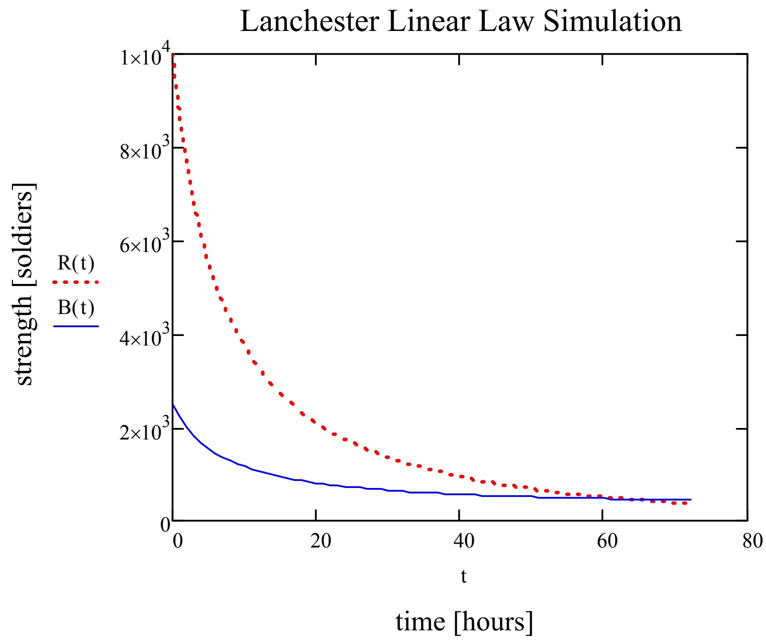


Figure 105: Lanchester linear law simulation for a friendly (blue) force infantry brigade opposing a threat (red) force division, an approximately 1:4 numerical ratio of forces. The threat force began the battle with 10,000 soldiers, while the friendly force began with 2,500 soldiers.

5.4 Concept of Electric Fires

Nearly a thousand 1,000 years ago, the Chinese documented the first use of gunpowder for military purposes. These early weapons consisted of bamboo tubes loaded with a tamped mixture of gunpowder and shrapnel-producing materials.[205] Almost a millennium later, ground combat warriors rely on the same basic technology of burning propellant and harnessing the pressure of expanding gases to launch projectiles across the battlefield. There is a compelling vision to revolutionize the weapons of warfare by using electrical energy as the basis for power generation.[206] Concepts and technologies in this area abound, ranging from fully mature fielded systems to what may be considered the lunatic fringe of science fiction.

In the emerging frontier of electromagnetic weaponry, the Chinese appear to have once again championed a new military technology by being the first country to proclaim this developing concept as the future domain for warfare. In a 2010 paper from the International Electromagnetic Launch (EML) Symposium, Wang Ying, the president of the Chinese EML Association, defined four generations of weaponry: mechanical energy or cold weapons (swords, bows and arrows), chemical energy weapons (firearms), nuclear energy weapons (bombs), and the class currently under development which he broadly called electromagnetic weapons. To quote from his treatise, Wang states that "at present, it is the Chinese who firstly disclose the law of scientific development of armament to the world, namely, the fourth-generation weaponry is the electromagnetic

[205] Jacques Gernet, translated by J.R. Foster and Charles Hartman, *A History of Chinese Civilization* (Massachusetts: Cambridge University Press, 1996) 311.
[206] Richard A. Marshall, "Railgunnery: Where Have We Been, Where Are We Going?" *IEEE Transactions on Magnetics*, Vol 37, No 1, January 2001, 440-444.

weaponry."[207] He goes on to further describe five distinct classes of electromagnetic weapons including electromagnetic kinetic energy, electromagnetic pulse, artificial intelligence, information weaponry, and electromagnetic interference weapons.[208]

5.4.1 Types of Electric Fires Weaponry

The types of electromagnetic weapons emerging from this developing domain can alternatively, and preferably, be organized under the general classification of Electric Fires, or devices that transform electrical energy into a desired effect on a target of interest.[209] This broad framework, seen in Figure 106, arranges the advanced concepts in a complementary and nested hierarchy that shares electrical energy as the source for power generation and creation of target effects. With the exception of the launcher class that use electromagnetic forces to accelerate a payload, the types of weapons in the Electric Fires domain each exist in a band of the electromagnetic spectrum depicted in Figure 107. Of particular interest for ground combat systems is the prospect of using electromagnetic forces to accelerate projectiles.

[207] Wang Ying and Jiange Zhang, "Electromagnetic Launch Leading to Electromagnetic Weapon Era" *2010 International Electromagnetic Launch Symposium* (Brussels, Belgium: IEML, 2010) 1-8.
Two years prior, Matt Cilli of the (former) Army Railgun program gave an award winning IEML presentation on the evolution of tactical weapons throughout history. He classified the four types of throw energy as being human, mechanical, chemical, and electromagnetic (future). Wang's paper expounded on this generational framework, elevating the construct to the strategic level and broadening the scope to include all classes of electromagnetic weaponry beyond simple launch or throw devices.

[208] Ibid., 1-8.

[209] Electric Fires is not a doctrinal term, however this title has been used in several conference settings and seems to capture the essence of creating target effects with electrical energy as the prime source for the transformer or weapon.

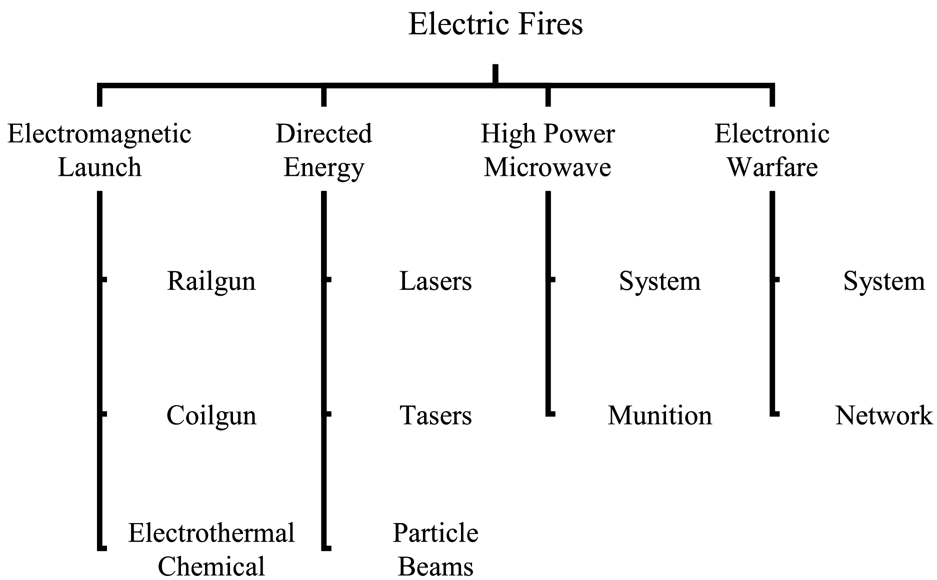


Figure 106: Electric fires organizational framework.[210]

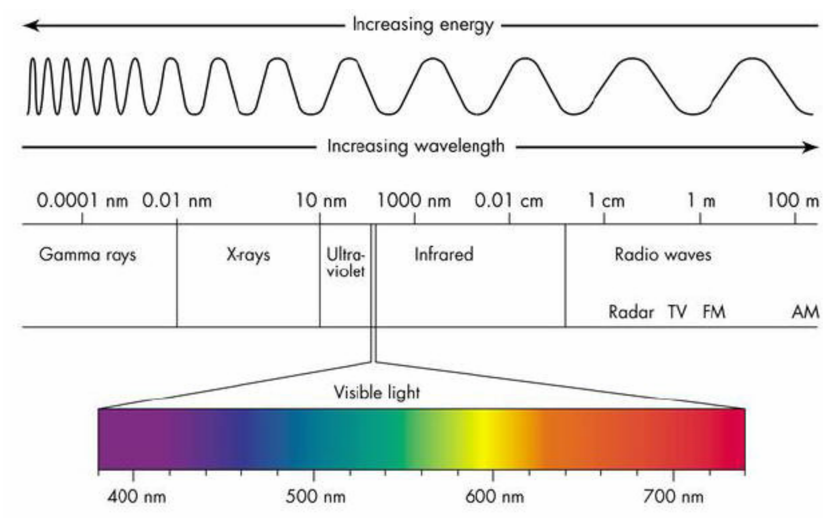


Figure 107: Electromagnetic spectrum. Note the relationship between wavelength and energy.[211] Source for the graphic is www.antonine-education.co.uk.

[210] For an excellent review on directed energy fundamentals, see *Laser Weapons*: *The Dawn of a New Military Age* by Bengt Anderberg and Myron Wolsbarsht (New York: Plenum Press, 1992). *Beam Weapons: The Next Arms Race* by Jeff Hecht (New York: Plenum Press, 1984) provides a historical reference to this emerging domain of weaponry, mostly from a Cold War context.

5.3.2 Electromagnetic Launch

When considering the key cannon performance metric of muzzle velocity, electromagnetic launchers have achieved muzzle velocities beyond the theoretical limits of a tactical powder cannon, with laboratory launchers routinely achieving 2.4 km/s.[212] In these velocity regimes, dense penetrators can deposit specific energy levels commensurate with high explosives. The expanding gases in a conventional powder gun operate on velocity scales on the order of the sound speed of the working fluid inside the bore. The theoretical velocity limit for these expanding gases is approximately of 5 – 8 km/s, with practical limits for a tactical launcher in the 1.5 to 2.0 km/s range.[213]

5.3.2.1 Kinetic Energy versus High Explosive

As an example of the criticality of projectile velocity with respect to target effects, consider two target interactions, one kinetic and one chemical–explosive (Figure 108). In this figure, a 1 kg long rod penetrator encountering a target at 3 km/s deposits 4.5 MJ of kinetic energy on the target (KE = $\frac{1}{2}mv^2$, (½ of 1kg at $(3000\text{m/s})^2$ = 4,500,000 J). Similarly, 1 kg of high explosive (e ≈ 4.5 MJ per kg) releases a similar amount of energy on the target. While the gross amounts of energy brought to the target are commensurate, the kinetic energy is much more efficient at insulting the target than the free expansion of blast induced pressure from the release of chemical energy (90% versus 10%).[214] In other

211 Doug Beason, *The E-Bomb: How America's New Directed Energy Weapons Will Change the Way Future Wars Will Be Fought* (Cambridge, Massachussetts: De Capo Press, 2005) 20-28. This book classifies directed energy as including microwave and laser technologies.
212 R.M. Ogorkiewicz, Technology of Tanks (United Kingdom: Jane's Information Group, 1991) 93.
213 R. Heiser, "Gasdynamic Limits of Maximum Attainable Muzzle Velocities for Conventional Guns" *5th International Symposium on Ballistics* (Toulouse, France, 1980) 234-249.
214 Harry D. Fair, *Electromagnetic Launch Short Course*, hosted by the Institute for Advanced Technology at Austin Texas, July 23-26, 2007, slides 11-14.

words, the net energy deposited into the target with kinetic energy is greater, since a larger fraction of energy deposited with the chemical energy munition is lost to expansion in free space.

At hypervelocity, on a specific energy or equivalent mass perspective, inert projectiles can deposit energy proportional to the yield attained by high explosive materials. There are many challenges associated with attaining bullet speeds in excess of 2 km/s. There are also significant handling requirements and transportability issues associated with contemporary ammunition that rely on the release of chemical energy to both accelerate and, in some cases, insult a targeted threat.

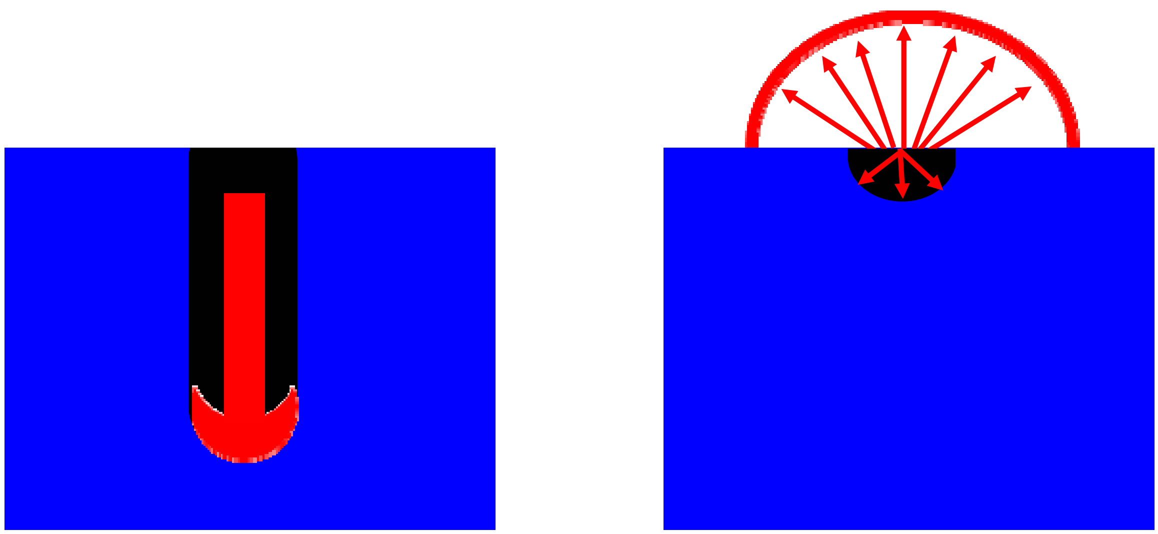


Figure 108: Kinetic energy (KE) on left and chemical or high-explosive (HE) energy on right interacting with a notional target (blue block of RHA). Crater volume from the KE interaction is approximately an order of magnitude greater than the HE. Dr. Harry Fair provided a discussion and graphics that served as the source for the creation of this figure.

5.3.2.2 Electromagnetic Launch Railguns

In the division of Electric Fires known as electromagnetic launch, the competing class of these future weapon concepts is called the railgun.[215] Named for the parallel conductors or rails that form the working surface of the launcher, the function of a simple railgun can be considered as that of a one-turn, linear, direct current (DC) motor.[216] As current flows down a conducting rail, it generates a magnetic field around the rail. As the current crosses perpendicularly through this magnetic field across a bridging element, in this case an armature that is free to move, a Lorentz force is imparted into the armature as well as any launch package mated to it. Since the armature is free to move, the launch package can be propelled down the length of the cannon. In this way, the current continues to flow back down its companion parallel rail, imparting a force onto the launch package until the circuit is opened, normally occurring when the armature has departed from the muzzle of the railgun and the current has fully diffused.

[215] I.R. McNab, "Early electric gun research" *Magnetics, IEEE Transactions*, Jan 1999 Volume: 35, Issue: 1, 250 – 261. McNab provides a thorough historical review of the 100+ years of electric gun research.
[216] Wang Ying, Richard Marshall, and Cheng Shukang *Physics of Electric Launch* (Beijing, China: China Machine Press, 2004) 21.

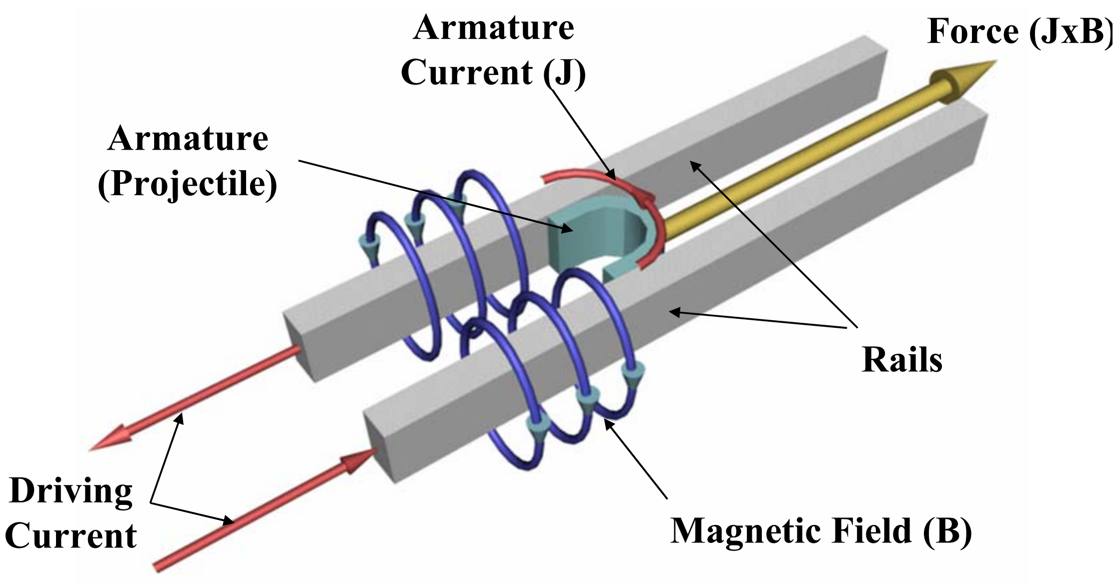


Figure 109: Railgun schematic illustrating the propelling Lorentz force generated in the region where the current (J) crosses the magnetic field (B). The armature is considered free to slide along the rails.[217]

Through virtual-work analysis, the force imparted to the projectile in a simple, solid armature, one-turn railgun, takes the familiar form of Equation 54, where L' is a electromagnetic bore geometry parameter called the inductance gradient with units of microhenries per meter squared ($\mu H/m^2$), and I is the current with units of amperes. As explained by Marshall, "in an ordinary motor there are hundreds of turns so the current is used hundreds of times as it were. With the [simple] single-turn railgun, the current is used once so it must be hundreds of times higher to enable reasonable propelling forces to be obtained."[218] For a tactical launcher designed for a ground combat vehicle, peak current values are on the order of megaamperes (MA), a level necessary to generate muzzle energies in the megajoule (MJ) range. Given that the launch event occurs in 5-10

[217] Harry D. Fair, "Electromagnetic Launch Fundamentals" *Electromagnetic Launch Short Course*, hosted by the Institute for Advanced Technology, Austin, Texas, July 23-26, 2007.
[218] Richard A. Marshall and Wang Ying, *Railguns: Their Science and Technology* (Beijing, China: China Machine Press, 2004) 5.

milliseconds (ms), the peak power discharge is in the gigawatt (GW) range. For a ground combat system, therein lies the engineering problem: how to efficiently store MJ levels of energy, generate GW levels of power (for very short, pulsed durations), and direct MAs of current to create tactically significant levels of launch energy.

$$F = \frac{1}{2} L' I^2 \qquad \text{Equation 54}$$

With some appreciation for the technical challenges associated with creating a tactical railgun system (critical path element being the power supply and related switching), the first question one may ask is why launch projectiles electromagnetically? The short answer is speed. At the tactical level, for direct fire cannons, electromagnetic launch yields increased lethality, since penetration efficiency is a strong function of impact velocity. For indirect fire cannons, higher muzzle velocity yields both greater maximum effective range (MER) and higher impact velocity.

At the operational level, there may be a reduction in logistical demands since electromagnetic launch munitions do not require any propellant or powder charge. This can equate to substantial savings in transport requirements since for ordnance velocity rounds (muzzle velocities of 500–1500 m/s), the powder charge is approximately half the mass of the projectile. Additionally, a concept based on the transformation of electrical energy can, in theory, accept multiple sources for energy storage and power discharge.

At the strategic level, railguns could yield greater specific cannon energy, as well as a scaleable and tunable weapon system that could reduce collateral damage and act in concurrence with the proportionality tenet of Just War Theory. In the next two sections, the opportunities and challenges of pursuing electromagnetic launch are further explored using the survivability, lethality, and mobility construct for direct fire systems. To provide a balanced alternative, a conventional powder gun system with evolutionary capability is also presented.

5.5 Advanced Direct Fire Powder Gun and Railgun Systems

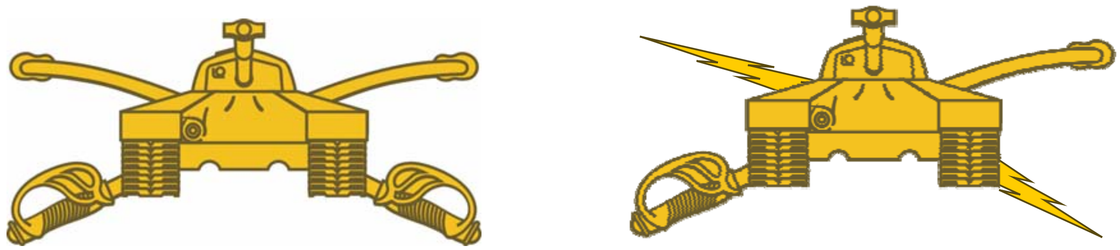


Figure 110: Armor branch insignia, standard (left) and as modified by the author (right). The modified insignia replacing a saber with a lighting bolt signifies electric fires.[219]

The analysis for the direct fire engagement scenario was conducted in reverse sequential order against a notional advanced threat vehicle (Figure 111). The starting point focused on the terminal ballistic event, or the finale of the meeting engagement.

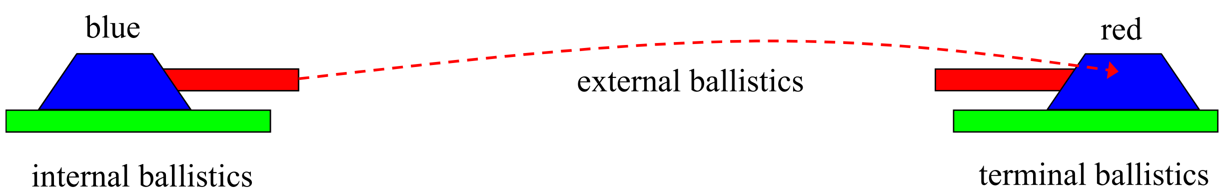


Figure 111: Notional direct fire engagement consisting of a terminal, external, and internal ballistic event.

The terminal ballistic event began as the projectile contacted the target and ended when the projectile had transferred all available energy to the threat system. The objective for the terminal ballistic event was to perforate the threat armor, a requirement in generating an insult conducive with destroying the system. The next step was external

[219] Source for unmodified armor branch insignia graphic is http://en.wikipedia.org/wiki/File:Armor-Branch-Insignia.png.

ballistics analysis. This stage analyzed projectile travel through the atmosphere from muzzle departure to imminent target impact. The goals for the external ballistic event were to fly quickly and accurately to the target. These first two steps were done irrespective of the launch source. The last step in the direct fire analysis focused on internal ballistics. Internal ballistic analysis began with commission of a lethal payload and ended with impending departure of the payload from the muzzle. The internal ballistic analysis was done for both an advanced powder gun and railgun concept. A unique launch package design for both powder gun and railgun was developed using best practices. Additionally, a powder gun and railgun cannon system, to include magazine, and power supply (for the railgun concept) was also theoretically constructed.

5.5.1 Target Effects and Terminal Ballistics

Beginning with terminal ballistic analysis, a review of historical development and recent design trends served to guide the generation of technical requirements. The predominant improvement in terminal ballistic performance since the end of World War II has been on achieving higher penetration efficiency through increased impact velocity.[220] In the early 1950s, the U.S. military demonstrated target impact penetration of up to 660 mm (over 2 ft) of rolled homogeneous armor (RHA). This was done at relatively low impact velocities (800 m/s), very high impact energies (300+ MJ), and incredibly large amounts of propellant energy (1000+ MJ).[221] To illustrate the magnitude of this energy, a 4,000 lb car smashing into a brick wall at 75 mph has approximately 1 MJ of kinetic energy at the moment of impact.

[220] W. Lanz, W. Odermatt, G. Weihrauch, "Kinetic Energy Projectiles: Development History, State of the Art, Trends" *International Symposium of Ballistics,* TB-19, May 2001, 1192-1197.
[221] Ibid., 1192-1193.

When considering the performance from the 1950s, modern tank caliber kinetic energy penetrators match this 660 mm depth, but with much higher efficiency. For example, a large caliber, direct fire bullet, like the M829 armor piercing, fin stabilized, discarding sabot (APFSDS) round fired from 120 mm M256 cannon found in the M1 Abrams series main battle tank, impacts at nearly a mile a second (1600 m/s). To achieve 660 mm of penetration, the faster impact requires only 2% of the kinetic energy on target than the earlier example (6 MJ versus 300 MJ). Interestingly, the local system efficiency, or the ratio of impact kinetic energy to incident chemical energy, is actually lower with the high velocity case. Approximately 40 MJ (9 kg at 4.4 MJ per kg) of propellant are required to generate the muzzle velocity commensurate with 6 MJ of energy on target in the high velocity projectile. However, the current system achieves that penetration depth with 9 kg of propellant, compared to the 1950s setup which needed 250 kg. In other words, the high velocity design is able to transfer each MJ of impact energy into 110 mm of penetration, while the lower velocity case gets only 2 mm of penetration per MJ.

For two main reasons, this is not an entirely fair comparison. First, the 1950s example is based on a laboratory fixture wholly unsuited for tactical application. Second, several other key design features have jointly contributed to improved penetration performance. For example, additional advances in penetrator design, including the use of denser materials, lighter sabots, and high aspect ratio penetrators (ratio of length of penetrator to the diameter of the penetrator), have also helped increase penetration depth. Even with these concessions, the fact remains that the most dominating factor in target penetration has been impact speed and its related effect on penetration efficiency.

5.4.1.1 Penetration Efficiency

The factor that impact velocity plays with penetration efficiency becomes evident when constant energy impact events are plotted as a function of velocity using the Lanz/Odermatt/Jenquartier equations, one of which is presented as Equation 55.[222] In this equation, P is the depth of target penetration, L_w is the penetrator length, λ is the ratio of penetrator length to penetrator diameter, θ is the angle of obliquity for target impact (a.k.a. the NATO angle), m_{NATO} is the exponent for plate inclination (assumed as 0.225), ρ is the material density for penetrator (subscript p) and target (subscript t), v_p is the impact velocity, and R_m is the target material tensile strength. The variable c is found using Equation 56, and the term for $f(\lambda)$ is found using Equation 57, where a_1 equals 3.94 and a_2 equals 11.2. When material properties are assumed for standard target and penetrator design (Table 47), this produces the classic s-shape curve seen in Figure 113. Figure 114 includes a similar curve overlaid with data points for nearly 100 ordnance and hypervelocity impact experiments.

$$P = L_{\mathrm{w}}\left(f(\lambda)\cdot(\cos\theta)^{-m_{\mathrm{NATO}}}\cdot\sqrt{\frac{\rho_{\mathrm{p}}}{\rho_{\mathrm{t}}}}\cdot e^{\left(\frac{(-c\cdot R_{\mathrm{m}})}{(\rho_{\mathrm{p}}\cdot v_{\mathrm{p}}^{2})}\right)}\right) \qquad \text{Equation 55}$$

$$c = 21.1 + 12.74\times10^{-9}R_{\mathrm{m}} - 9.47\times10^{-18}R_{\mathrm{m}}^{2} \qquad \text{Equation 56}$$

$$f(\lambda) = 1 + a_1\times\frac{1}{\lambda}\left(1-\tanh\left(\frac{\lambda-10}{a_2}\right)\right) \qquad \text{Equation 57}$$

[222] Held, Manfred, "A Tutorial on the Penetration of Kinetic-Energy (KE) Rounds" *Journal of Battlefield Technology,* Vol. 7, No. 1, March 2004, 1-8. This is an excellent overview of KE impact physics.

Table 47: Target and Penetrator Properties

constants	**value**
$\rho_{penetrator}$	18000 kg/m^3
ρ_{target}	8000 kg/m^3
R_m	1000 MPa
a_1	3.94
a_2	11.2
m_{NATO}	0.225

Figure 112: Proxy vehicles used to develop notional threat armor packages. Pictured on the left is the Russian T-80UM2 “Black Eagle”. On the right is the Russian BMPT-2 “Terminator”. [223]

[223] Source for the T-80 tank graphic is www.tankzone.co.uk, and the source for the BMPT-2 IFV graphic is www.armyrecognition.com/russia_russian_army_ bmpt_bmp.html

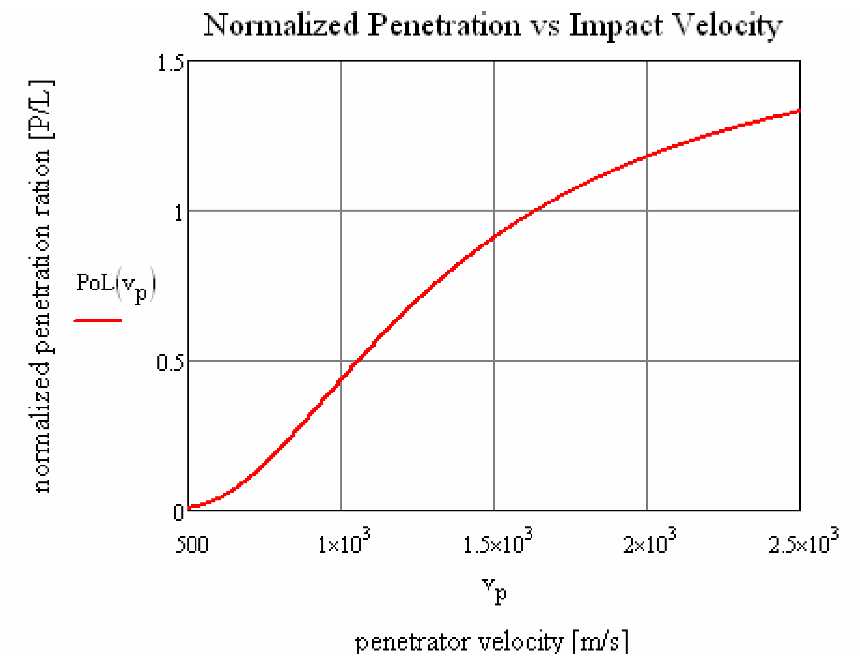


Figure 113: Normalized penetration as a function of impact velocity.

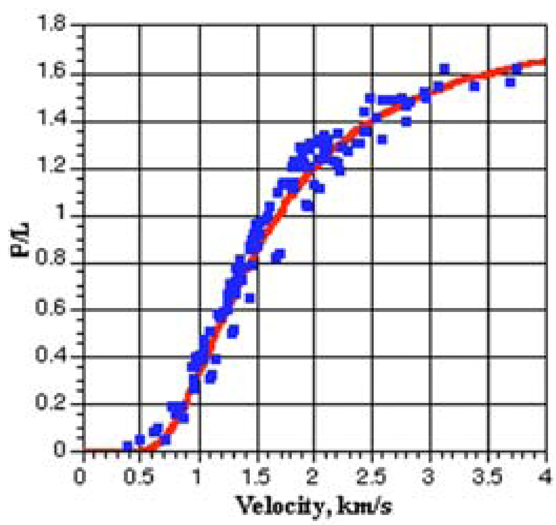


Figure 114: Experimental values of normalized penetration (P/L) as a function of impact velocity. [224, 225]

[224] V. Hohler and A.J. Stilp, "Penetration of Steel and High Density Rods in Semi-Infinite Steel Targets" *3rd International Symposium on Ballistics*, Karlsruhe, Germany, H3: 1-12, 1977.

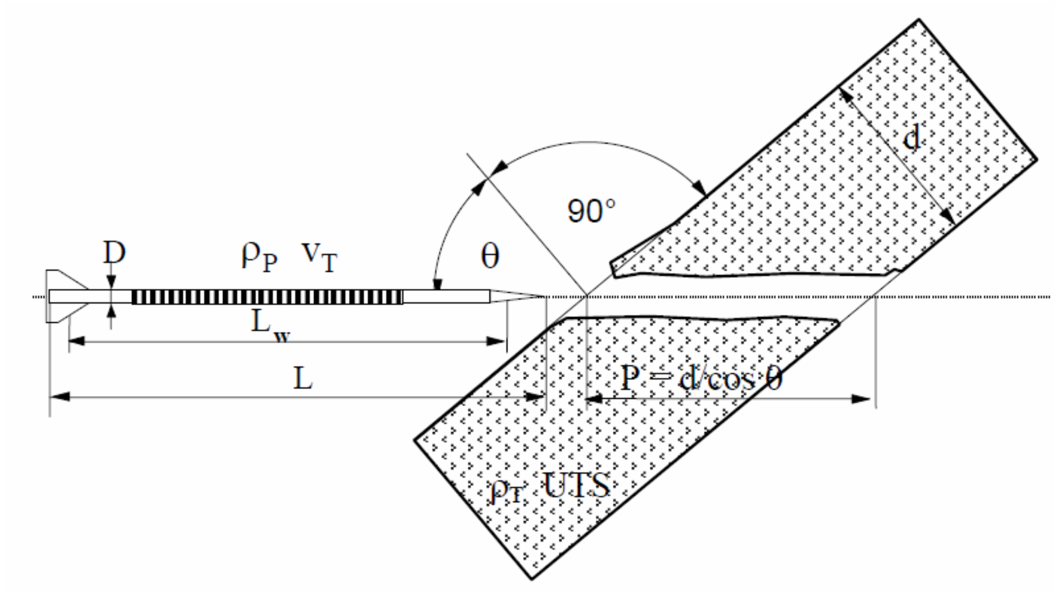


Figure 115: Terminal ballistic schematic from Lanz and Odermatt (2000) depicting long rod penetrator impacting target at an oblique angle.[226]

An exhaustive review by de Rosset and Amico on the experimental results of kinetic energy projectiles over a wide range of velocities, aspect ratios, and scales, found that an impact velocity of 2050 m/s was optimal for high aspect ratio (L/D = 30) direct fire penetrators.[227] Assuming armor penetration requirements for an advanced tank and IFV (P = 1000 mm and 100 mm of RHA respectively) at a NATO angle of 60°, Equation 55 was used to calculate the optimal penetrator length.[228]

[225] W. Lanz and W. Odermatt, "Penetration Limits of Conventional large Caliber Anti Tank Mines / Kinetic Energy Projectiles" *13th International Symposium on Ballistics*, Stockholm Sweden, Vol. 3, 225-233, 1992.
[226] W. Lanz and W. Odermatt, "Minimum Impact Energy for KE Penetrators in RHA Targets", European Forum on Ballistics and Projectiles, St. Louis, France, April 2000.
[227] William S. de Rosset, and D. Andrew D'Amico, "Optimum Velocity Penetrators", *Defense Technical Information Center*, 1995, 7.
[228] Lanz and Odermatt, 2000. This paper also calculated optimal impact velocities. The authors concluded that the optimal velocity was considerably slower than de Rosset and D'Amico calculated, but they also only considered powder gun launches which induce higher peak acceleration during launch requiring more sabot structural mass.

5.4.1.2 Behind Armor Debris

At this point, given its high density and identification as a likely replacement for conventional depleted uranium penetrators, a tungsten penetrator slug was designed to ensure perforation of the armor on the proposed set of advanced fighting vehicles, i.e., a tank and IFV with protection equivalent to 1000 mm and 100 mm of RHA respectively. For rounds with an aspect ration of 30 (λ), the high density slugs are depicted in Figure 117, and accompanying specifications for each are provided in Table 48. It should be noted that these values are just for the lethal mass of the penetrator designed to perforate the armor. In addition to demonstrating increased penetration efficiency with hypervelocity, it has also been shown that behind armor debris increases with impact velocity. Behind armor debris "significantly contributes to the incapacitation of personnel and damage of internal components of armored vehicles subjected to perforating impacts by kinetic energy penetrators."[229]

At constant impact energy, this debris appears to increase in quantity and over a larger solid angle at higher velocity.[230] The debris cloud can be considered as a truncated ellipsoid composed of fragments radiating outwards from the point of armor perforation. In experimental tests, a series of thin plates (referred to as "witness packs") are arranged behind the target. These plates provide forensic evidence of the behind armor debris emanating from the target hole. As impact velocity increases, the maximum emission angle (θ_{max}), number of fragments, and fragment perforations at successive plates, all

[229] Edward W. Kennedy and David L. Diehl, "Behind-Armor Debris Produced by DU-3/4Ti and WHA Penetrators at Ordnance and Higher Velocities" Army Research Laboratory Technical Report 3784, May 2006, 1-3. WHA stands for tungsten (chemical symbol W) heavy alloy. WHA is a formulation designed for penetrators.

[230] C. Anderson, Jr., S. Bless, T. Sharron, and R. Subramanian, "Behind Armor Debris Comparisons at Ordnance and Hypervelocities" TARDEC Combat Vehicle Survivability Symposium, Monterey, California, 1995.

increase.[231] Each fragment has a unique mass, trajectory, and velocity, which at best can be modeled stochastically based on verification with experimental results.

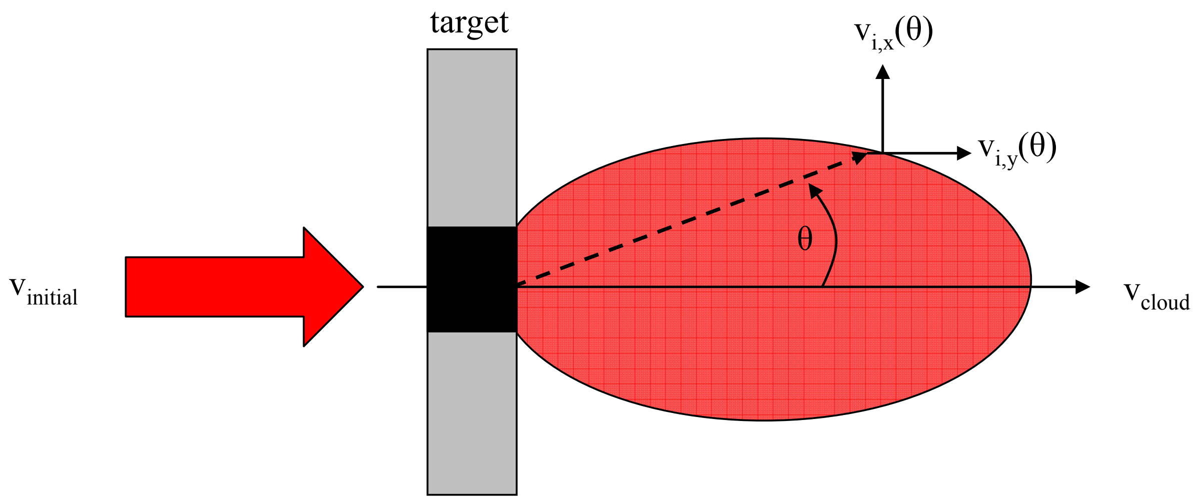


Figure 116: Schematic depicting generation of behind armor debris cloud (truncated red ellipse) consisting of target and projectile fragments radiating outward.[232]

[231] J.L. Verolme, M. Szymczak, "Behind-Armour Debris Modeling for High-Velocity Fragment Impact" *17th International Symposium on Ballistics*, Midrand, South Africa, March 1998, 259-265.

[232] Ibid. This figure was generated based on the generally accepted depiction of a truncated ellipse forming the behind armor debris field extending from the crater of target penetration.

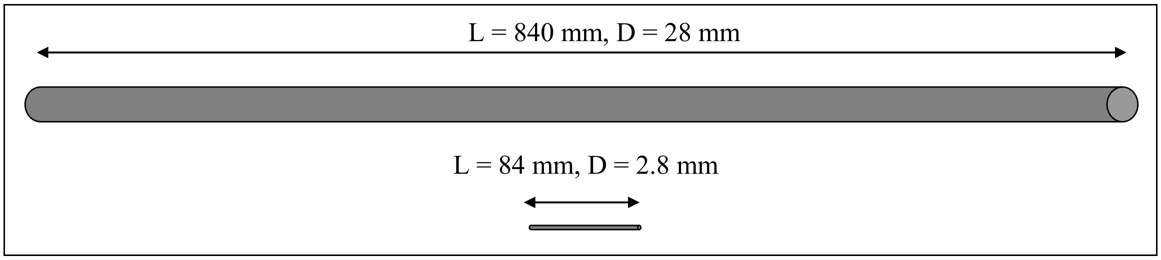


Figure 117: Penetrators for advanced tank target (top) and advanced IFV target (bottom) designed to penetrate 1000 mm and 100 mm of RHA respectively.

Table 48: Hypervelocity Tank and IFV Tungsten Penetrator Specifications

Specification	Variable	Tank round	IFV round
penetration depth	P	1000 mm	100 mm
length of penetrator	L	840 mm	84 mm
diameter of penetrator	D	28 mm	2.8 mm
mass of penetrator	m	7 kg	700 g
kinetic energy of penetrator	KE	16 MJ	1.6 MJ

5.5.2 Target Engagement and External Ballistics

Assuming an engagement at 2,000 m and drag induced deceleration determined from Equation 58, Equation 59 was used to calculate a required muzzle velocity of 2134 m/s, rounded up to 2150 m/s. In Equation 58, ρ is the density and the subscript p and ∞ are for the penetrator and atmosphere respectively. The coefficient of drag, C_d is assumed as 0.15. If the impact velocity (v_{imp}) is set at 2050 m/s, then Equation 58 and Equation 59 can be solved simultaneously to find the deceleration per km (v') and required muzzle velocity (v_{muz}). The bullet leaves the muzzle at approximately Mach 6, and for the relatively short flight the deceleration occurs in the supersonic range. Therefore, one can assume a constant drag coefficient in this equation.[233] This agrees with the aeroballistic kinetic energy penetrator deceleration rule of thumb of 50 m/s loss in velocity for each km of flight.[234]

$$v' = \frac{1}{2}\frac{\rho_\infty}{\rho_{\text{p}}} \cdot C_{\text{d}} v_{\text{muz}} \frac{1}{L} \qquad \text{Equation 58}$$

$$v_{\text{muz}} = v_{\text{imp}} + v' \cdot r \qquad \text{Equation 59}$$

$$L_{\text{opt}} = e^{\frac{1}{3}} \frac{P}{f(\lambda)\left(\cos(\theta)\right)^{m_{NATO}} \sqrt{\dfrac{\rho_{\text{p}}}{\rho_{\text{t}}}}} \qquad \text{Equation 60}$$

$$m_{\text{p}} = \rho_{\text{p}} L \pi \left(\frac{L}{\lambda}\right)^2 \qquad \text{Equation 61}$$

In order to sustain proper orientation downrange from a smoothbore cannon, a titanium nose cone and set of six stabilizing fins was designed based on a proven design in the M829 series of APFSDS kinetic energy rounds (Figure 119). A simplifying assumption was that the leading edge is a simple high aspect ratio cone. In actual practice, this critical feature requires a more sophisticated profile (e.g., von Kármán or parabolic nose cone).[235]

[233] S.S. Chin, *Missile Configuration Design* (New York: McGraw Hill, 1961) 23-36.
[234] Held, 1-3. Another useful rule of thumb comes from this paper which estimates the length of long rod penetrator as a function of the square of the ratios of penetrator and target densities.
[235] S.S. Chin, *Missile Configuration Design* (New York: McGraw Hill, 1961) 23-36.

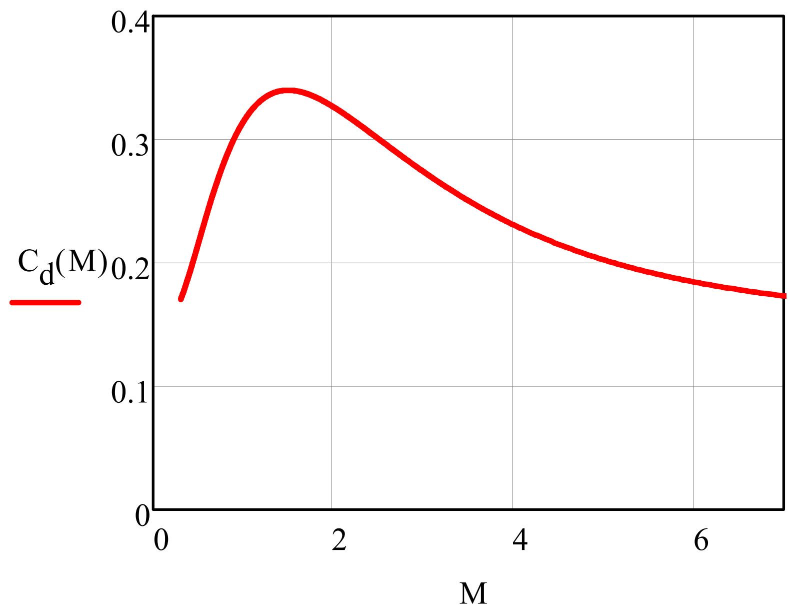


Figure 118: Drag coefficient as a function of Mach number for typical hypervelocity aeroshell utilizing a von Kármán nosecone, tubular body, trailing boattail, and clipped delta wing stabilizing fins.[236]

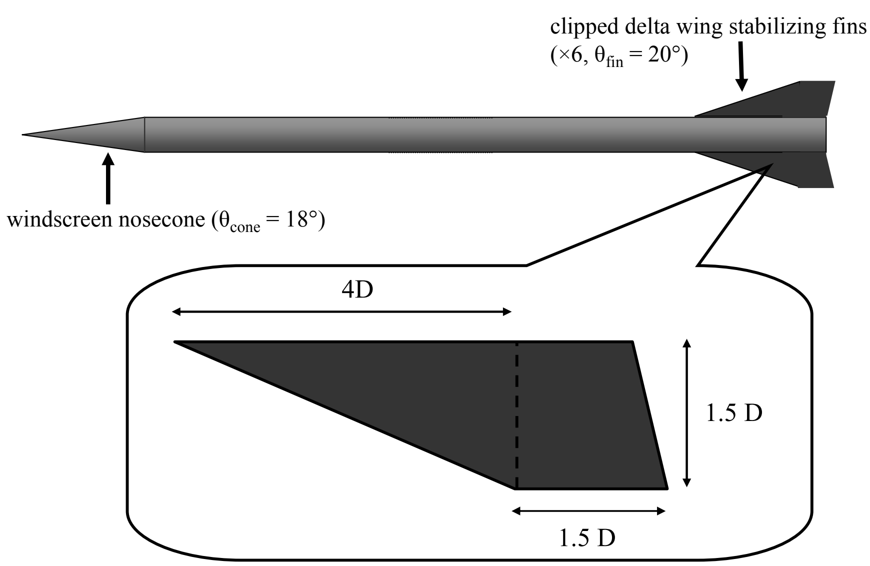


Figure 119: Kinetic energy long rod penetrator with titanium windscreen nosecone and clipped delta wing stabilizing fins.

[236] Robert L. McCoy, *Modern Exterior Ballistics: The Launch and Flight Dynamics of Symmetric Projectiles* (Penssylvania: Schiffer Publishing, 1999) 72-77.

The design and construction of the flight body (nose and fins) is a critical component that ensures the penetrator reaches the target accurately and efficiently. Assuming thin gauge titanium is used for the flight surfaces, the mass is surprisingly small for a standard cone and set of six fins (257 g and 3 g for the tank and IFV round respectively).[237] This mass for nose cone and fins was subsequently accounted for in the exterior and interior ballistic calculations.

5.4.2.1 Time of Flight and Lag Time

The last aspect of external ballistics analysis considered dealt with time of flight and lag time. Time of flight is the time required to travel from muzzle to target. Assuming constant drag, time of flight can be calculated from Equation 62. In Equation 62, v_{muzzle} is the muzzle velocity, k_1 is a constant found using Equation 65, and r is the range to the target. In Equation 65, ρ_{atm} is the atmospheric density, $A_{\text{projectile}}$ is the cross sectional area of the projectile, C_D is the coefficient of drag for the projectile, and $m_{\text{projectile}}$ is the mass of the projectile. Lag time (Equation 63) is the "time difference, or lag between the actual flight time and the time to the same range in a vacuum."[238] This lag time is used to calculate crosswind induced deflection in the classical formula presented in Equation 64. In Equation 64, $w_{crosswind}$ is the wind speed normal to the trajectory.

[237] B.P. Burns, L. Burton, and W.H. Drysdale, "Methodologies for Forecasting Sabot Mass for Advanced Gun and Projectile Systems" *Ballistic Research Laboratory Technical Report*, BRL-TR-3387, June 1991, 4-5. The authors provide a rule of thumb tare weight for stabilization devices of 150–250 g. The produced values (257 g) agree with this provided tare weight value.
[238] Robert L. McCoy, *Modern Exterior Ballistics: The Launch and Flight Dynamics of Symmetric Projectiles* (Pennsylvania: Schiffer Publishing, 1999), 159-160.

$$t_{\text{flight}} = \frac{1}{v_{\text{muzzle}} k_1}\left(e^{k_1 r} - 1\right)$$ Equation 62

$$t_{\text{lag}} = t_{\text{flight}} - \frac{\text{r}}{v_{muzzle}}$$ Equation 63

$$w_{\text{deflection}} = w_{\text{crosswind}} t_{\text{lag}}$$ Equation 64

$$k_1 = \frac{\rho_{\text{atm}} A_{\text{projectile}} C_{\text{D}}}{2 m_{\text{projectile}}}$$ Equation 65

5.4.2.2 Crosswind Deflection

To explore the effect of high impact velocity on crosswind induced drift and time of flight, a parametric sweep of muzzle velocity at constant muzzle energy was conducted. In this case, 10 MJ were made available for launch, with 2 kg dedicated to parasitic mass.[239] The parasitic mass ratio is the fraction of mass of the loaded launch package that does not travel to the target. The range for muzzle velocity was from 1500 to 2500 m/s. The range to the target was 2000 m, and a constant crosswind of 10 m/s (22 mph) was assumed. The aspect ratio (λ) was set at 30. The penetrator mass as a function of velocity was found using Equation 66, where E_{muzzle} is the muzzle energy of the cannon. The diameter and cross sectional area of the penetrator as a function of velocity were found using Equation 67 and Equation 68. The terminal velocity of the penetrator as a function of velocity was found using Equation 69.

[239] At 1500 m/s, this mass represents the current fraction required to sustain launch. The assumption was made that as the velocity increased and the lethal payload decreased (constant energy), that this supporting mass would sustain launch at higher velocity but lower projectile mass.

$$m_{\text{penetrator}}\left(v_{\text{muzzle}}\right)=\frac{2E_{\text{muzzle}}}{v_{\text{muzzle}}^{2}}-m_{\text{parasitic}} \qquad \text{Equation 66}$$

$$d_{\text{penetrator}}\left(v_{\text{muzzle}}\right)=\sqrt[3]{\frac{4m_{\text{penetrator}}\left(v_{\text{muzzle}}\right)}{\pi\rho_{\text{penetrator}}\lambda}} \qquad \text{Equation 67}$$

$$A_{\text{penetrator}}\left(v_{\text{muzzle}}\right)=\frac{\pi d_{\text{penetrator}}^{2}\left(v_{\text{muzzle}}\right)}{4} \qquad \text{Equation 68}$$

$$v_{\text{terminal}}\left(v_{\text{muzzle}}\right)=\frac{2m_{\text{penetrator}}\left(v_{\text{muzzle}}\right)g}{C_{\text{D}}\rho_{\text{atm}}A_{\text{penetrator}}\left(v_{\text{muzzle}}\right)} \qquad \text{Equation 69}$$

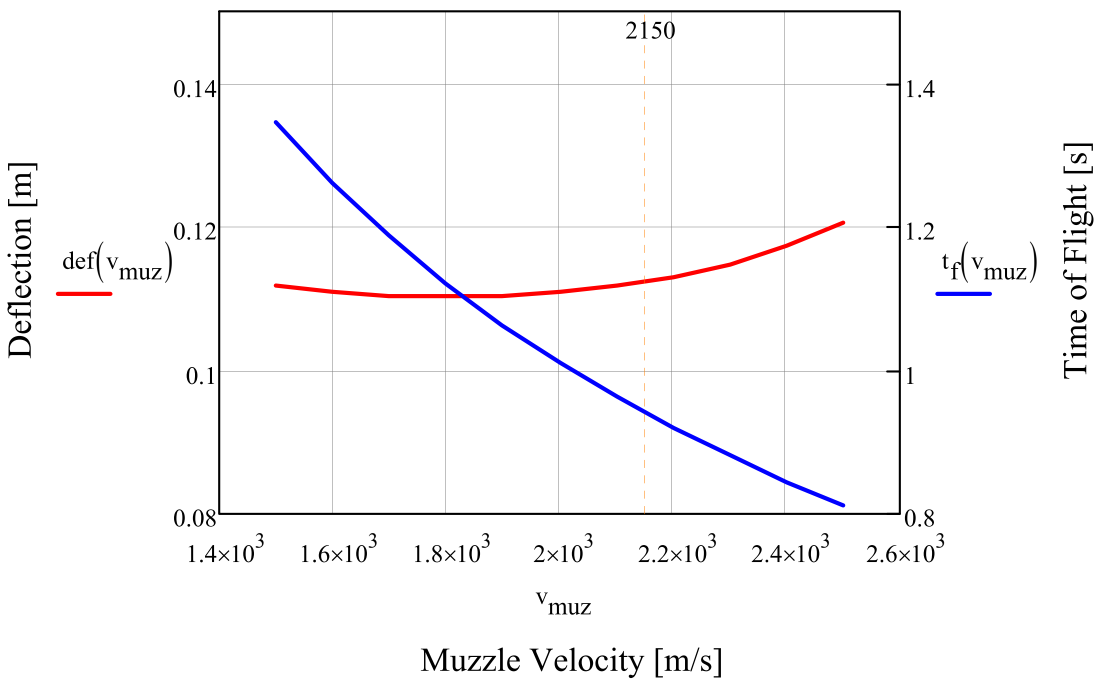


Figure 120: Target deflection and time of flight versus muzzle velocity for a constant energy cannon. Crosswind speed is 10 m/s, and muzzle energy is held at 10 MJ with 2 kg of the launch package dedicated to parasitic mass. The y-axis is the fraction of deflection off of a 1 m^2 target area.

5.5.3 Target Acquisition and Internal Ballistics

The last step in the examination of advanced direct fire systems was to conduct internal ballistic analysis. This was done in three main areas. First was design of the cartridge (powder gun) and integrated launch package (railgun). For a powder gun, the cartridge consisted of a penetrator carried in a mid-drive configuration with discarding sabots set in a combustible shell casing packed with propellant (Figure 121). For a railgun, the launch package consisted of the same penetrator carried by a mid-drive armature and discarding sabots (Figure 122). Next was the cannon or launcher barrel design. Cannon length for the large caliber round was fixed at 6 m and for the medium caliber round it was set at 3 m. An advanced composite overwrap was considered for both the powder gun and railgun design (Figure 124 and Figure 125). Lastly was embodiment of the ammunition magazine (powder gun) and the ammunition storage area with power supply (railgun). Based on prior work, the bore for the tank round powder gun was assumed to be 140 mm (20 mm greater than the current NATO standard tank gun 120 mm ammunition).[240] The powder gun designed to propel the advanced IFV round was assumed to be 35 mm.[241] A previous design effort was used to create the railgun system for the tank round with a 90 mm round bore.[242] Likewise, the railgun envisioned to

[240] Asher H. Sharoni and Lawrence D. Bacon, "The Future Combat System (FCS): Technology Evolution Review and Feasibility Assessment, Part Two- Armament" *Armor Magazine*, (Sep-Oct 1997) 29-35. The 140 mm design was originally conceived under the ARDEC XM291 Advanced Tank Cannon program (ATAC).

[241] Jerome T. Tzeng and Edward M. Schmidt, "Comparison of Electromagnetic and Conventional Guns from a Mechanics and Material Aspect" *23rd International Symposium on Ballistics*, Tarragona, Spain (16-20 April 2007) 597 – 604. In this paper, the authors compare the existing Mauser Mk 30-2 firing the Oerlikon PMC287 kinetic energy projectile with a comparable railgun with a 14.5 mm × 32.7 mm rectangular bore.

[242] J.J. Hahne, J.L. Upshaw, J.H. Herbst, J.H. Price, "Fabrication and Testing of a 30 mm and 90 mm Laminated, High L′ Railgun Designed and Built at CEM-UT" *IEEE Transactions on Magnetics*, Vol 31, no. 1, January 1995, 303-308.

propel the advanced IFV round had a 15 mm round bore. This was comparable to the revered M2 Browning 0.50 caliber machine gun in bore size (12.7 mm versus 15 mm).[243]

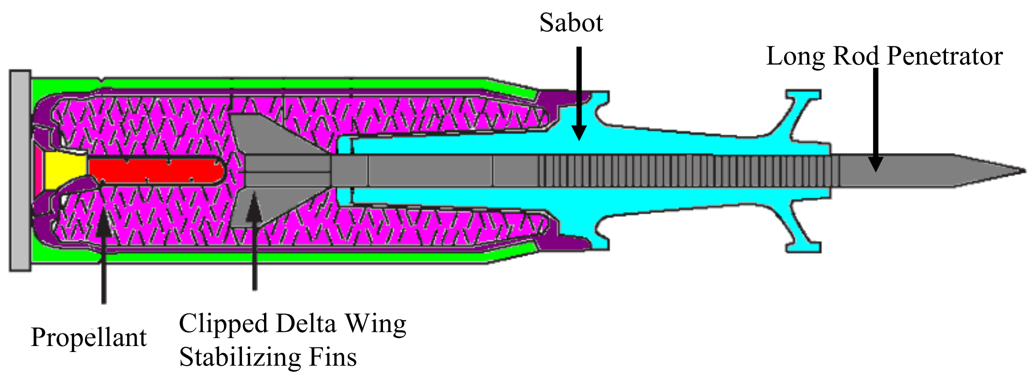


Figure 121: Kinetic energy cartridge based on M829 series round.[244]

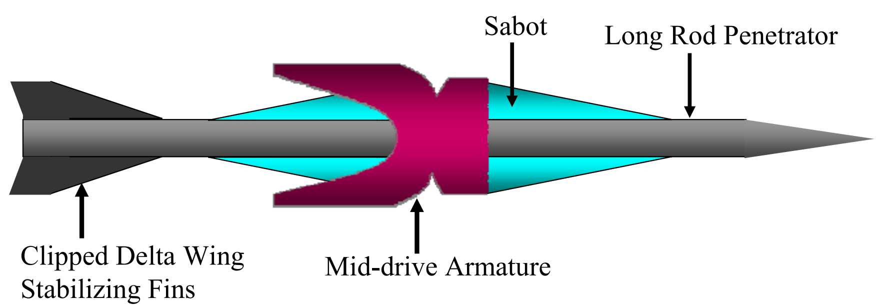


Figure 122: Hypervelocity kinetic energy integrated launch package.

To design the structures (sabots, obturator, and bore riders) required to support the subcaliber, long rod penetrator during its journey down the powder gun, the closed-

[243] R. A. Marshall, "Railgun bore geometry, round or square?" *IEEE Transactions on Magnetics*, Jan 1999, 427-431.
[244] Source for unshaded graphic is www.inetres.com/gp/military/cv/weapon/M256.html

form design formulas developed by Burns, Burton, and Drysdale were used (Equation 70 and Equation 71).[245] In these equations, c is the mass of the propellant charge, P is the breech pressure, d_{sp} is the diameter of the penetrator plus twice the groove height, A_1 is a design constant ($A_1 = 0.000087$), and L_f is the length of the flight body. For the railgun launch package, values developed independently by British and U.S. exploratory design effort were used.[246, 247] For conventional cannons at high ordnance velocities (1500 - 1700 m/s), contemporary parasitic mass ratios are 0.45, and values as low as 0.3 are achievable using advanced sabot materials and novel fabrication methods.[248] However, as velocity is increased into the hypervelocity regime (2000 m/s), the parasitic mass ratio climbs back up to the half-fraction range. The supporting structures, which contribute to the parasitic mass, scale with the inertial forces during the extremely violent launch event. High velocity powder guns have a high piezometric efficiency normally in the 50%–60% range.[249] Piezometric efficiency (ε_p) is the ratio of average pressure to peak pressure during the launch event.[250] The peak to average acceleration ratio is the inverse of ε_p. A muzzle velocity commensurate with hypervelocity launch requires high peak pressure for as long as possible, therefore the parasitic mass ratio will also be high.

[245] B.P. Burns, L. Burton, and W.H. Drysdale, "Methodologies for Forecasting Sabot Mass for Advanced Gun and Projectile Systems" Ballistic Research Laboratory Technical Report, BRL-TR-3387, June 1991.
[246] M.M. Hinton, N.R. Coooper, D. Haugh, and M.A. Firth, "On the Parasitic Mass of Launch Packages for Electromagnetic Guns" *10th U.S. Army Gun Dynamics Symposium*, ADA404787: 2001, 291-304.
[247] Alexander E. Zielinski, "Integrated Launch Package Design With Considerations for Reduced-Scale Demonstration" *IEEE Transactions on Magnetics*, Vol. 39, No. 1, January 2003, 402-405.
[248] M.M. Hinton, N.R. Coooper, D. Haugh, and M.A. Firth, "On the Parasitic Mass of Launch Packages for Electromagnetic Guns" *10th U.S. Army Gun Dynamics Symposium*, ADA404787: 2001, 292.
[249] Donald E. Carlucci, Sidney S. Jacobson. *Ballistics: Theory and Design of Guns and Ammunition*. New York: CRC Press, 2007, 94-96.
[250] Ibid.

$$m_{\text{launch package}} = m_{\text{penetrator}} \left(1 + A_1 \left(\frac{D_{bore}}{d_{\text{penetrator}}} \right)^2 \left(\frac{1}{1 + \frac{c}{2m_{\text{launch package}}}} \right) \left(\frac{P_{\text{breech}}}{\rho} \right)^{0.532} \right) \qquad \text{Equation 70}$$

$$\rho = \frac{4m_{\text{penetrator}}}{\pi d_{\text{sp}}^2 L_{\text{f}}} \qquad \text{Equation 71}$$

Railguns can achieve higher muzzle velocities with a lower ε_p. The electromagnetic force applied to the launch package is finely controlled by the switching and discharge of the power supply. However, the parasitic mass ratio for a railgun launch package includes the armature or the sliding electrical bridging structure that forms a circuit between the two rails. This critical component subjected to millions of amperes of current flow and 100+ kgees (1 kgee = 1,000 g or 1,000 × 9.81 m/s^2) of acceleration is designed to perform several functions. Therefore, the mass advantage given to a railgun launch package for lower peak acceleration values is offset by the multifunctional requirements of the armature for the launch event. For the kinetic energy penetrator carried by a mid-drive armature with supporting sabots and front bore riders, the railgun parasitic mass ratio is again in the half-fractional range.[251, 252] Therefore, for both the powder gun and railgun launch package, the parasitic mass ratio was assumed to be 0.5.

[251] M.M. Hinton, N.R. Coooper, D. Haugh, and M.A. Firth, "On the Parasitic Mass of Launch Packages for Electromagnetic Guns" *10th U.S. Army Gun Dynamics Symposium*, ADA404787: 2001, 302-303. Depending on the launch phase (internal, external, and terminal), the parasitic mass ratio is defined differently. For example, some elements that travel downrange to the target do not contribute to the penetration event and therefore are sometimes considered to be parastitic mass (aeroshell, fins, tracer cartridge). Within this chapter, the author considered the parasitic mass ratio to be the fraction of internal ballistic support structures divided by the total launch package mass.

[252] R.J. Hayes and T.E. Hayden. "Experimental Results from Solid Armature Tests at the Center for Electromechanics at The University of Texas at Austin Center for Electromechanics" *IEEE Transactions on Magnetics*, Vol. 29, No. 1, January 1993, 819-825. This paper presents results from a similarly designed 90 mm laboratory cannon firing a demonstration launch package with long rod penetrator.

This meant that each system would have to accelerate a mass equal to twice the penetrator from zero to 2150 m/s along the length of the respective barrel.

In order to design the propellant charge required to propel the bullet in the powder gun, a series of charge mass correlations were consulted. From Heiser and Horst, Equation 72 was used to determine the muzzle velocity for a given propellant charge *c*. In this equation, e_{charge} is the specific energy of the propellant, γ is the ratio of specific heats for the working fluid, and V is the volume of the barrel (V_o is the chamber volume and V_{muzzle} is the volume of the chamber and the length of bore). Using launch properties for the 120 mm M256 with an M829A2 APFSDS round, Equation 72 predicts a muzzle velocity of 1697 m/s versus 1650 m/s measured. Alternatively, Ogorkiewicz and Rhienmetall present muzzle velocity estimation solely as a function of the ratio of charge mass to launch package mass. In Ogorkiewicz version (Equation 73), m_c is the mass of the charge or propellant and m_p is the mass of the projectile. In the Rhienmetall estimation (Equation 74), ζ is a characteristic coefficient equal to 0.46, ε is a weighting factor equal to 0.5, and Q_{ex} is a property of the propellant equal to about 4 kJ per kg. Note that in Equation 74 the ratio of charge mass and propellant mass are in the denominator and are inverted. These two equations have been plotted across a range of mass ratios (φ_{mass}) for comparison (Figure 123). In the figure, v_{Og} is the Ogorkiewicz predicted velocity and v_{Rh} is the Rhienmetall predicted velocity with units of m/s. For a required muzzle velocity of 2150 m/s, the average mass ratio predicted is approximately 2.5. This means that a 1 kg projectile would require 2.5 kg of propellant in the cartridge.

As a comparison, the M829A2 firing at a muzzle velocity of 1670 m/s has approximately 9 kg of propellant for an 8 kg projectile. This projectile mass includes both the penetrator and the sabots. The Rhienmetall equation under predicts the muzzle velocity by less than 100 m/s. With this data, the values for the mass and volume of the powder gun cartridges and railgun integrated launch packages for the tank and IFV targets were calculated (Table 49). The calculated mass of the powder gun cartridge includes the penetrator, aeroshell, sabots, propellant, obturator, and combustible casing. The calculated mass for the railgun integrated launch package consisting of the penetrator, aeroshell, sabots, obturator, and mid-drive armature. The cartridge volume was estimated based on a scaled up M256 cannon with a larger bore (140 mm versus 120 mm) and bigger breech volume (183 mm diameter versus 156 mm). The breech is the oversized area at the base of the cartridge where the propellant begins to burn during the launch process. The integrated launch package volume was calculated based on a cylinder that would serve as the logistical transport tube for the launch package. This is a slightly oversized sleeve shape encompassing the 90 mm and 15 mm round bore railgun cannons.

$$v_{\text{muzzle}} = \sqrt{\left(\frac{2e_{\text{charge}}c}{\gamma - 1}\right)\left(\frac{1-\left(V_o - V_{\text{muzzle}}\right)^{\gamma}}{m_{\text{launch package}} + \frac{c}{3}}\right)} \qquad \text{Equation 72}$$

$$v_{\text{muzzle}} = 1500\left(\frac{m_{\text{c}}}{m_{\text{p}}}\right)^{0.45} \qquad \text{Equation 73}$$

$$v_{\text{muzzle}} = \sqrt{\frac{2\xi_{\text{e}}Q_{\text{ex}}}{\frac{m_{\text{p}}}{m_{\text{c}}} + \varepsilon}} \qquad \text{Equation 74}$$

Table 49: Powder Gun Cartridge and Railgun Integrated Launch Package Properties

	tank round		IFV round	
	mass [kg]	volume [cm^3]	mass [kg]	volume [cm^3]
Powder Gun	49	31,910	4.9	116
Railgun	14	6,362	1.4	19

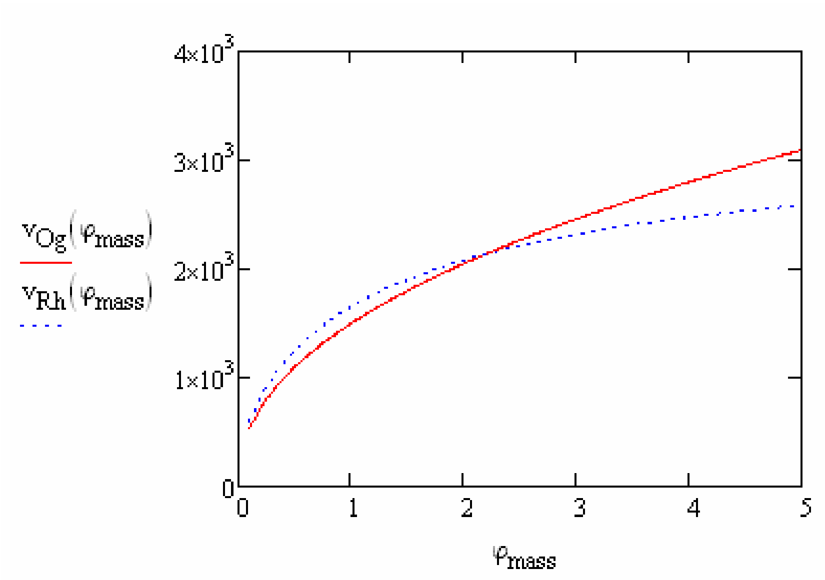


Figure 123: Predicted muzzle velocity using the Ogorkiewicz (v_{Og}) and Rhienmetall (v_{Rh}) equations as a function of the ratio of charge mass to projectile mass (φ_{mass}).

The next step was to design the powder gun cannon and railgun cannon which could support the launch of the projectiles. For the powder gun, a maximum chamber pressure of 700 MPa was assumed.[253] For the railgun design, an inductance gradient (L') of 0.55 μH per m was assumed. The average acceleration ($\overline{a}$) was found from Equation 75. In this equation, l_{bore} is the length of the bore. With this, the average and peak current I were found from Equation 76 and Equation 77 where $m_{launch\ package}$ is the mass of the

[253] Donald E. Carlucci, Sidney S. Jacobson. *Ballistics: Theory and Design of Guns and Ammunition* (New York: CRC Press, 2007) 5.2-5.4. This value is nearly 25% greater than the maximum chamber pressure of the 120 mm M256 cannon in the Abrams tank.

entire launch package and η is the average to peak acceleration (assumed as 0.75). With this peak current *I*, the pressure generated from the bore (P_{bore}) was found from Equation 78. Finally, the ratio of outer to inner radii (ζ_{bore}) was found from Equation 79 where σ_y is the yield strength of the containment material .[254] This closed-form solution is derived for a monobloc wall construction based on the Lamé equations for thick-walled, pressure vessel design. With this ratio and an assumed yield strength from a high-modulus, carbon fiber overwrap construction material, a powder cannon and railgun cannon were extruded in accordance with the cross section schematics depicted in Figure 124 and Figure 125.[255]

$$\bar{a} = \frac{1}{2}\frac{v_{\text{muzzle}}^2}{l_{\text{bore}}} \qquad \text{Equation 75}$$

$$\bar{I} = \sqrt{\frac{2m_{\text{launch package}}\bar{a}}{L'}} \qquad \text{Equation 76}$$

$$I_{\text{peak}} = \frac{\bar{I}}{\eta} \qquad \text{Equation 77}$$

$$P_{\text{bore}} = \frac{L'I^2}{A_{\text{bore}}} \qquad \text{Equation 78}$$

$$\zeta_{\text{bore}} = \sqrt{\frac{\sigma_{\text{y}}^2 + P_{\text{bore}}\sqrt{4\sigma_{\text{y}}^2 - 3P_{\text{bore}}^2}}{\sigma_{\text{y}}^2 - 3P_{\text{bore}}^2}} \qquad \text{Equation 79}$$

254 Carlucci makes an interesting observation in his text when he plots ζ_{bore} versus the ratio of chamber pressure and yield strength. As this P_{bore} over σ_y approaches 0.58, the ratio of inner and outer bore radii approaches infinity. In other words, the chamber pressure can never be greater than 58% of wall material yield strength.

255 Joshua Keena and Tess Moon, "Bore Configuration Analysis for a Direct Fire Railgun" *Classified Symposium on Electromagnetic Launch* (San Antonio, Texas, September 2009).

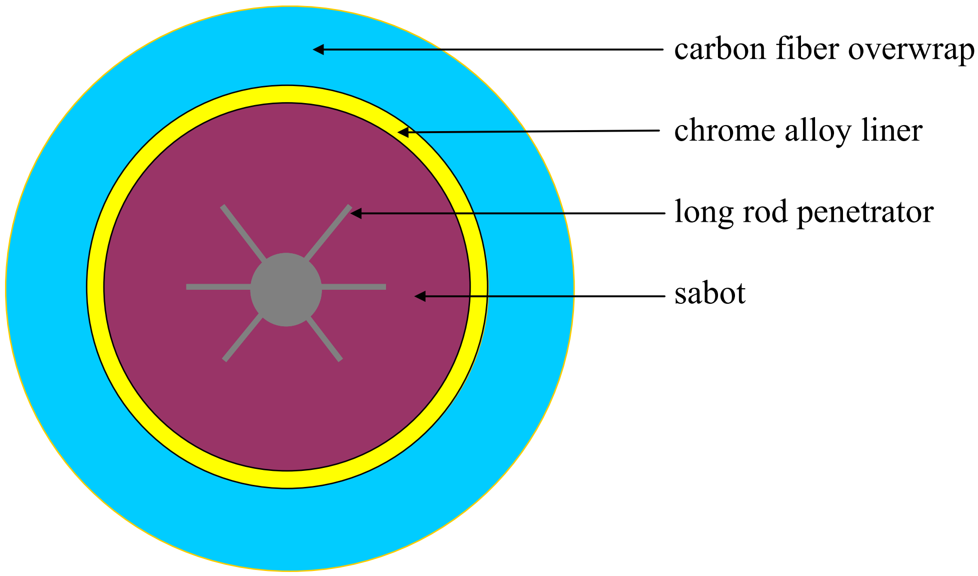


Figure 124: Powder gun cannon cross section schematic.

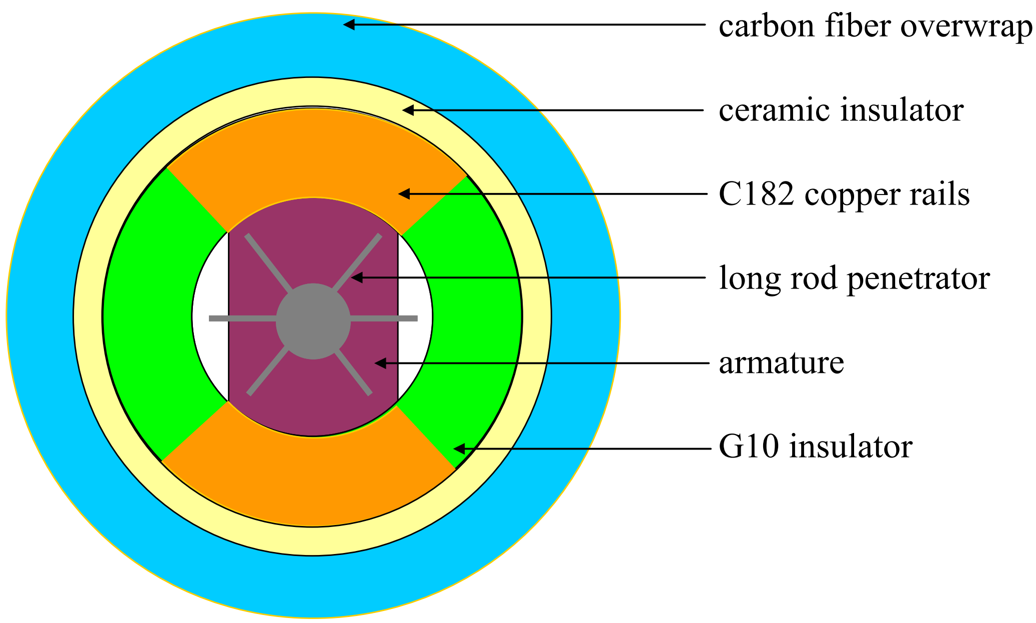


Figure 125: Railgun cannon cross section schematic.

Finally, to account for the railgun power supply, switching, and ancillary equipment, a spreadsheet modeling tool developed by Mallick and Crawford was used.[256] This program accepts a collection of weapon system and technical requirements, and produces an estimation for numerous aspects of the design of the composite system. The values for system mass and volume as they would directly impact a first-order analysis on fighting vehicle design were of greatest interest. The input parameters used for the simulation are provided in Table 50 (pulsed alternator and launcher), and the output values for the railgun system, as well as the design values for the powder gun system, are listed in Table 51.[257] As a cursory look at the advanced concepts presented, the cannon mass only considers the barrel, breech, and cabling (for railgun). The magazine is assumed to carry 40 tank rounds or 100 IFV rounds.

[256] John Mallick and Mark Crawford, *Launcher System Sizing Tool V16xFW*, Institute for Advanced Technology, Austin, Texas 2007.

[257] Ian R. McNab, "Pulsed Power Fundamentals" work supported by ARL DAAA21-93-C-0101, Institute for Advanced Technology, Austin, Texas, April 1996.

Table 50: Railgun Sizing Tool Input Parameters

Pulsed Alternator Parameters	**Units**	**Tank**	**IFV**
Maximum speed	rpm	11000	11000
Maximum B at stator winding	Tesla	3	3
Maximum tip speed	m/s	600	600
Maximum temperature rise/shot	K	30	30
Operating Banding Stress	ksi	700	450
Number of Alternators	#	2	2
Shot Rate	per minute	4	8
Desired Shots Stored	#	2	3
Muzzle Energy	MJ	32	3
Muzzle Velocity	m/s	2150	2150
Peak Acceleration	kgee	85	120
Piezometric Efficiency	#	0.75	0.65
Gun Efficiency	#	0.50	0.50
Inductance Gradient L'	μH/m	0.55	0.55

Table 51: Powder Gun and Railgun System Specifications[258]

Property	**140 mm powder gun**	**90 mm railgun**	**35 mm powder gun**	**15 mm railgun**
total mass [kg]	6,000	13,000	1,300	2,800
cannon mass [kg]	4,000	3,000	1,000	700
magazine mass [kg]	2,000	500	300	100
power supply mass [kg]	n/a	9,500	n/a	2,000

[258] All mass values have been rounded to the nearest 100 kg.

5.5.4 In-stride Assessment of Advanced Weapon System Concepts

At this point, neither tank cannon appears to be a good candidate. The problems with larger caliber (>125 mm) powder gun cannons are fairly well established and have been faithfully avoided to date. In other forums, the 140 mm concept has been presented internationally; perhaps reassuringly, this brief study converged on the same general scaling issues and design challenges. In essence, the pursuit of higher tank caliber lethality with a powder gun ends up producing a very heavy cartridge that necessitates either splitting the cartridge into two or more pieces (projectile and propellant) or designing an autoloader that can handle the round. The cannon and breech for the powder gun are also markedly higher as the operating pressure must be raised to attain the higher muzzle velocities. In physical terms, the cannon and complementary ammunition approach that of an artillery system, is wholly unsuited for a mobile and protected source of firepower like a ground combat vehicle.

(a) The 9-V battery has mass 45 grams.	220 kJ/kg
(b) Kinetic storage.	
The steel flywheel shown has mass 1.1 kg.	9 kJ/kg
High tensile steel ring.	90 kJ/kg
Carbon fiber ring.	1060 kJ/kg
(c) Spring. Energy density for a carbon fiber composite spring.	0.5 kJ/kg
(d) Rifle cartridge. Energy density for TNT ("nuclear number").	4.4 MJ/kg
(e) Hydrocarbon (diesel fuel). One-sixth thimble full.	42 MJ/kg
(f) Capacitor. The 10-kJ capacitor is large with volume 4 liters.	1.0 kJ/kg

Figure 126: Entities that contain 10 kJ of energy (Marshall, 2001).[259]

A final consideration in the analysis of an advanced, high velocity cannon concept involves the effect of muzzle velocity on recoil force. The larger the recoil force, the more equipment required to mitigate that force to minimize the vehicle motion and return

[259] Richard A. Marshall, "Railgunnery: Where Have We Been, Where Are We Going?" *IEEE Transactions on Magnetics,* Vol 37, No 1, January 2001, 440-444. This article describes the persistent challenges with railgunning as well as the progress made in the 1990s.

the cannon to battery after firing. “By conservation of momentum, a reaction is applied to the launcher that is equal and opposite to that of the projectile and any other inertia ejected out the muzzle.”[260] Railguns have the advantage of generating a relatively flat ballistic curve, which simplifies the analysis, while also serving as the best case for a powder gun. The case considered is a constant energy cannon with a constant recoiling mass (cannon and breech). Similar to the time of flight and target drift analysis as a function of muzzle velocity, recoil force was analyzed as a function of velocity. The cannon length was set at 6 m, and the muzzle energy held at 10 MJ. Recoiling mass was assumed at 2,000 kg. Muzzle velocity ranged from 1500 m/s to 2500 m/s. The governing equations for this analysis follow.

$$KE_{\text{muzzle}} = \frac{1}{2} m_{\text{launch package}} v_{\text{muzzle}}^2 \qquad \text{Equation 80}$$

$$E_{\text{muzzle}} = \int_0^l F dx = F \Delta x \qquad \text{Equation 81}$$

$$I = m\left(v_{\text{final}} - v_{\text{initial}}\right) \qquad \text{Equation 82}$$

$$I = \int_0^{t_{\text{final}}} F dt = \int_0^{t_{\text{final}}} \left(ma\right) dt = F \Delta t \qquad \text{Equation 83}$$

For a constant energy cannon system of fixed length, the force acting on the projectile over the range of velocities analyzed is 1667 kN. The impulse *I* imparted into the cannon, found with Equation 82, is a function of velocity and mass, and for a fixed energy system the mass is also a function of velocity ($m(v) = 2\times KE/v^2$). Once the impulse is known for the launch package, this can be imparted into the cannon (recoiling) mass to calculate the rearward velocity. Assuming a stroke length of 0.5 m, the force

[260] Eric L. Kathe, “Recoil Considerations for Railguns”, *IEEE Transactions on Magnetics,* Vol 37, No 1, 425-431.

required to retard the recoiling motion within the stroke length can be found and represents the recoil force or the force imparted to the trunion or cannon support immediately following the launch event.

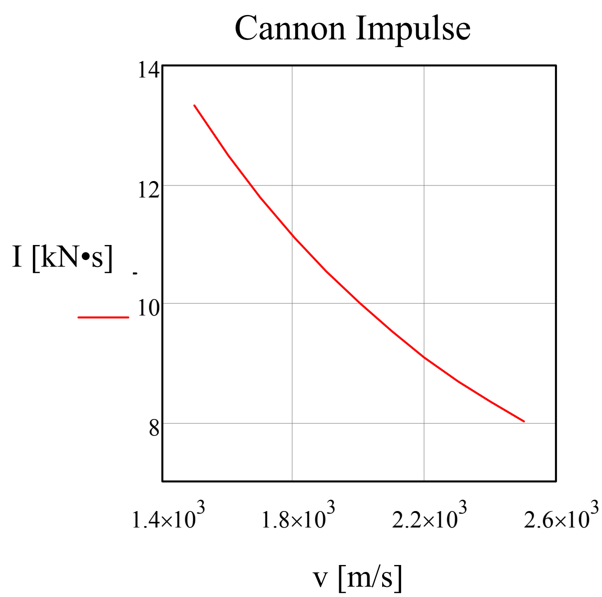


Figure 127: Cannon impulse as a function of muzzle velocity for a fixed length, constant energy system. Range of velocities is from 1.5 km/s to 2.5 km/s. Cannon length is 6 m, and muzzle energy is fixed at 10 MJ.

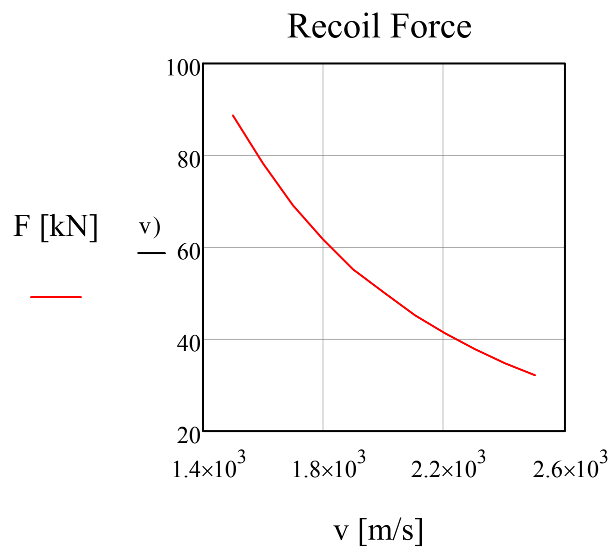


Figure 128: Recoil force as a function of muzzle velocity for a fixed length, constant energy system.

5.5.5 Medium Caliber Potential for Tactical Railguns

When facing an advanced tank target, neither the powder gun nor the railgun concepts appear to be attractive candidates. While the increased caliber of the powder gun may be undesirable for a ground combat system designed to defeat tanks, the railgun concept appears infeasible for a similar target end state. Given current technology, the mass and volume of the power supply present impracticable design penalties onto the railgun equipped platform. Put simply, entirely too much mass and a very large amount of volume must be dedicated to the power supply. The energy densities for the rotating machine electrical storage devices are several orders of magnitude lower than the propellant (Figure 126). Equipment required for power production and energy storage of 100+ MJ would dominate the vehicle.

With regard to the IFV cannon, investigating the railgun system designed to defeat an advanced IFV produces a challenging, but feasible candidate. The power supply and associated equipment for a medium energy weapon could theoretically be incorporated into a future combat platform. The railgun cannon system capable of generating 3 MJ generates a physically possible, albeit very technically challenging solution for an advanced direct fire weapon system. While the mass associated with the railgun system is almost 4 times greater than the powder gun, the railgun ammunition is only one quarter of the weight of the powder gun cartridges. For a similarly sized system, the railgun equipped fighting vehicle can carry more ammunition, while relieving the operational level of some materiel costs associated with ammunition resupply and the associated transport. Additionally, a vehicle based around a railgun could shed weight normally directed toward safe handling and storage of the ammunition. For example, the heavy compartmented areas (passive) and magazine fire suppression systems (active) would not be required at the level they currently are for a system designed around largely inert stores of ammunition.

5.6 Lessons Learned

- For a direct-fire cannon system, there are significant challenges associated with firing projectiles at hypervelocity. Powder guns require disproportionately large propellant loads to achieve marginal increases in velocity. Railgun power supplies are quite heavy and voluminous for a large-caliber mobile system. However, a medium-caliber railgun is a theoretically feasible candidate for an advanced weapon system designed to defeat advanced threat infantry fighting vehicles.
- Hypervelocity impact holds substantial benefit for both direct- and indirect-fire systems. The gains in lethality performance collectively generate greater effectiveness for an advanced concept direct fire weapon system, a requisite if one hopes to address the "quality versus quantity" issue predicted by the Lanchester Laws of Combat.
- With respect to target effects, hypervelocity impact enjoys greater penetration efficiency than an ordnance velocity event. Additionally, the behind armor debris (BAD) is considerably greater for a hypervelocity impact projectile.
- With respect to engagement, hypervelocity reduces the time of flight between muzzle and target. For a constant energy system under steady crosswind conditions, there is a minor increase in deflection off target at hypervelocity, correctable with proper sensing apparatus and an appropriate ballistic solution.
- With respect to the launcher system, for a tank cannon concept (30+ MJ), the powder gun ammunition cartridge and barrel become impractical for a hypervelocity concept. For a railgun design, while the integrated launch package is quite compact, given current manufacturing technology and material properties, the power supply is infeasible in both mass and volume.
- The 3 MJ IFV railgun system appears to be a feasible candidate. The railgun weapon system mass is four times that of a conventional system, but the ammunition is less than 25% as heavy and occupies much less space. Additionally, this power supply could be repurposed for an advanced 120 mm mortar system with double the range of a conventional system.

5.7 Conclusions

Advanced weapon concepts that can provide greater performance will require significant investment. Powder guns may be approaching the physical limits of practical muzzle velocity for a tactical system. Railguns, while offering substantial increases in muzzle velocity, require considerable weight dedicated to a power supply and switching equipment. The question then is whether to invest in an incremental improvement at the margins of a conventional technology, or to explore the potential advancements of a disruptive, unproven technology like electromagnetically launching projectiles.

In either case, higher muzzle velocity yields benefit at each stage of lethality analysis. At the target, higher velocity increases penetration efficiency, meaning a projectile can create deeper penetration. Moving through the target, hypervelocity has been shown to increase behind armor debris (BAD), a substantial contributor of lethal effects in target subsystem interaction.

When evaluating the external ballistics, higher velocity clearly reduces flight time. For a long-range engagement, this can mean greater weapon effectiveness, both in a single engagement (shooting before receiving insult) and in multiple engagements (switching rapidly to various targets). For a constant energy case, higher velocity did not contribute to substantial drift off target.

At the launcher, neither the tank railgun cannon nor the tank powder gun seemed to be good hypervelocity candidates. The powder gun cartridges are too large, and the power supply for the railgun is too large, both in mass and volume. However, the medium energy, 3 MJ railgun power supply appears feasible. This level of kinetic energy would be sufficient to service a range of targets, to include advanced IFVs, medium tanks, and moderately fortified bunkers. Additionally, since the muzzle energy of a railgun cannon is controllable, this weapon concept would provide crewmembers with a scaleable and tunable source of firepower. Moreover, as the propulsion of the railgun projectiles do not require a chemical propellant, crew safety would be increased by the removal of this source of potential sympathetic detonation and deflagration.

A power supply of this order could also conceivably be used for an advanced mortar system. The current 120 mm mortar fires a 13 kg projectile with a peak muzzle velocity of just over 300 m/s. Conventional mortars can fire out to a maximum range of just over 7 km. A DARPA-funded project successfully demonstrated cantilever railgun launch of a modified 120 mm round at speeds in excess of 500 m/s (2 MJ launch energy). Increasing the muzzle velocity to the limits of available power could double the range of this potent indirect-fire weapon system beyond what is presently capable using a conventional powder charge propellant. A shared design between a direct-fire and indirect-fire railgun power supply could be used on both an advanced direct fire and improved large-caliber mortar platform.

In summary, achieving advanced capability in any form will be an expensive, challenging, and risky endeavor. The pursuit should be in a direction that offers the highest theoretical limits, versus working at the margins of mature technologies. At another level of analysis, electromagnetic launch concepts demonstrate great advantage at the operational level through the compactness and safety afforded by the inert launch packages. At the same time, conventional powder gun enhancements aimed at creating greater lethality or range seem to further burden the operational level's supply network with larger cartridges and greater amounts of incendiary propellant.

Chapter 6: Summary and Conclusions

> Here in America we are descended in blood and in spirit from revolutionists and rebels - men and women who dare to dissent from accepted doctrine. As their heirs, may we never confuse honest dissent with disloyal subversion.
>
> —*Dwight D. Eisenhower*

6.1 Motivation Revisited

Soldiers serving in the U.S. Army genuinely appreciate the simple benefits afforded by good decisions and good design. Leaders that can formulate superior decisions generally employ soldiers in a more effective manner. Those good decisions can also contribute to the more efficient use of an organization's resources, a benefit made more essential today in light of the prevalent constraints of the contemporary operating environment, both in terms of financial and human resources. When evaluating the simple tools, as well as the most complex systems, furnished to troops in the U.S. Army, good design generally makes the soldier's ability to complete tasks and accomplish missions that much easier, again a welcome relief in light of the high operational tempo persistent in the contemporary operating environment.

With respect to ground combat vehicles, it was the humble intention of this research to contribute, even in an incremental fashion, to furthering considerations for, and quality of, the technical decisions regarding the design and selection of advanced ground combat vehicles. The general approach was to explore several novel avenues, all aimed at improving the chances for success in the seemingly intractable problem of designing and selecting an advanced ground combat vehicle. The engineering domain of a fighting vehicle is characterized by a high degree of technical challenges, as well as competing demands, all made more salient considering the life and death implications involved with a tactical engagement with the enemy. This work also recognized that engineers do not work in vacuums: engineers may recommend, but they rarely decide.

6.2 State of the Art

The historical review of military technological pursuits highlighted the persistent, apparently timeless, challenges associated with developing and adopting novel concepts in a government organization, defined by bureaucracy and constrained by rigid processes. While one may regard the contemporary operating environment as being exceptionally tested—in terms of balancing an array of competing demands, working under high levels of uncertainty, and reacting too slowly to development opportunities—these conditions appear to be more the norm than the exception in the two-plus centuries defining U.S. military history. For example, after demonstrating individual weapon performance superiority in virtually every measurable way, i.e., reloading time, accuracy, weight, etc., it still took the U.S. Army over five decades to replace muzzle loading muskets with breech loading rifles. While not an excuse to accept the status quo, it does help to place current challenges in a historically relevant context.[261]

What does appear distinctly different in the contemporary operating environment is the increasing rate of change in the evolution of warfare. Attributable to factors such as globalization, networked organizations, and the near-instantaneous sharing of information, the pace of development in military affairs shows evidence of hastening. The threats faced by the U.S., operating within a global network and engulfed in a massive, virtually instantaneous exchange of information, have pushed the speed of growth and continue to challenge traditional processes for technology developers. This, in turn, has demanded more robust materiel solutions, better postured to react to the higher levels of uncertainty observable on a rapidly evolving battlefield. In other words,

[261] For a maritime example of a missed opportunity regarding a revolutionary technology, see the John Ericcson and his experience with the Britich Navy rejecting his twin-screw propeller design.

there is greater demand for adaptation in even what may be regarded as evolutionary design efforts. The demand for effective and efficient materiel solutions developed over shorter design cycles necessitate decision support tools that can assist decision makers in pursuing the most bountiful and well-founded prospects over a timescale commensurate with addressing the requirement in a judicious and responsible manner.

When considering the post 9/11 focus on stability operations, again a historical perspective has value. Contrary to what may be popular belief, the history of the U.S. Army has been largely characterized by stability operations, highlighted with participation in eleven wars, all of which were necessitated by real threat to national security. These wars were precipitated by a peer challenger postured in discord to U.S. national interest.

In looking forward, the most probable course of action will be continued participation in stability operations, or those often described as “Small Wars”. But to be prepared for major combat operations, this persistent effort must be balanced with, at a very minimum, sustainment of conventional capabilities vigilantly forged and expertly honed over decades to address to the most dangerous course of action, those that imperatively involve the U.S. militarily in major combat operations. However, as this (thankfully) unlikely event (full-scale war) is also the most threatening (most threatening to national security), the portfolio of advanced development concepts should also include enhancing and expanding those capabilities aimed at facing the conventional scenarios depicted by major combat operations.

Related to the current focus on stability operations, contemporary requirements appeared to be defined more by mysteries than puzzles. While puzzles can be considered as well-defined, loosely or formally structured problems to which there is presumably a solution, mysteries deal with more ill-defined, still evolving, hence poorly structured problems to which there is likely no definitive solution. Unsurprisingly then, current developmental efforts focused on major combat operations revolve around addressing puzzles, while the focus on creating and sustaining military power in support of stability operations is largely centered on addressing mysteries. Stated differently, within the puzzle-mystery continuum, major combat operations are positioned at a more pronounced position on the puzzle axis, while stability operations are placed higher along the mystery axis. For materiel developmental pursuits intended to function well in both realms, concerted attention should be given to functioning in both the puzzle- and mystery-dominated arenas. Related to the rapid pace of evolving needs, materiel solutions need more inherent robustness to help underwrite the high uncertainty associated with future pursuits in an environment often largely characterized by mystery.

Products of a puzzle-solving era, the U.S. Army legacy systems (Abrams tank, Bradley fighting vehicle) are a tribute to foresight and technical effort during the Cold War. Although these platforms took decades to design and field, they have reigned supreme on the battlefield in several wars and countless operations. Somewhat disappointingly, vehicle design pursuits in the post Cold War era have not been as fruitful. The Stryker, lauded for its superior transportability, has been criticized for lacking sufficient protection and firepower. The family of Mine Resistant Ambush Protected (MRAP) vehicles provide crews with a highly survivable platform that has no organic weapon system. More troubling, the mass and overall dimensions of early MRAP variants imbued them with poor mobility over most forms of complex terrain. Additionally, the high survivability is mostly a function of acquired invulnerability due to armor appliqués that besiege the platform and create a highly susceptible system.

In both cases, remedial efforts were subsequently conducted in an attempt to bring some semblance of what may be referred to as attribute "balance" to these platforms. For example, the Stryker was the recipient of several armor upgrade packages. Also, more recently, better accepted versions of the MRAP have been somewhat smaller, and have also been upgraded in theater with both weapon system and optics equipment.

The U.S. Army's major developmental program, the Future Combat System (FCS) was cancelled outright due to a myriad of concerns, including cost overruns and a general uncertainty regarding the contribution such systems would make in future warfare. The ground combat vehicle (GCV) program, the succeeding effort focused on the replacement infantry fighting vehicle, has twice been postponed (August, 2010, January 2011) due to issues involving the performance requirements and capabilities of this advanced combat platform. The recent failures and cancellations with respect to fighting vehicle pursuits, while not entirely unique in the history of military programs, do present an alarming pattern, made all the more so by the rapidity of design evolutions and the conventional pursuits of peer threat nations, which operate in a manner unconstrained by a commitment to stability operations in the Middle East. In fact, the recent poor track record of U.S. Army ground combat vehicle pursuits motivated this research.

In an effort to contribute to the state of the art with respect to fighting vehicle design and selection, the field of decision analysis was surveyed, as it has been exercised in previous military efforts to good effect. This discipline offers an array of techniques and approaches designed to enrich the quality of decision making events. The analytic hierarchy process and related methods were useful in capturing decision maker attribute weighting values in a networked, echeloned fashion.

With regard to the theory, science, and engineering associated with fighting vehicles, a rich record of combat vehicle design theory and technical reference was found, but it appears to have peaked in volume during the Cold War. Notable contributions are attributed to R.M. Ogorkiewicz, as well as the U.S. Army Materiel

Command's voluminous production of a vehicle design handbook series. A 21st century updated version of these handbooks would serve future designers with reference material, refreshed to account for advances in the physical sciences, as well as to reflect the significant changes in fighting vehicle design requirements, design methods, and manufacturing techniques.

6.3 Ground Combat Vehicle Design Characteristics and Operational Considerations

Notably, the considerable art of decision analysis is not in simply choosing the methodically determined best candidate among a set of alternatives. Rather, the greatest contribution a decision analyst can provide to a decision maker is in the creation of unique alternatives that are in accord with an organization's higher-level, underlying principles. Identifying these fundamental principles is a step sometimes overlooked in decision analysis. Often the focus is to build an attribute hierarchy upward from the primary objective without looking downward at the essence of the pursuit. Just like trees need roots, a sound approach to developing a decision support network branching upward (limbs) from the design objective (trunk) must include an investigation directed downward (roots) to unearth the guiding principles and underlying doctrinal basis for the endeavor.

In this manuscript, the formation of the roots for the decision-analysis hierarchy, tree network included a review of the elements of combat power, the requirements for full spectrum operations, and an appraisal of the principles of war. The review of the doctrinal framework for U.S. Army operations served to strengthen the argument for the perpetual need of ground combat systems that can provide crews with enhanced levels of protection, firepower, and movement on the battlefield. Continual participation in stability operations immediately following the decisive actions in major combat in Iraq and Afghanistan have overshadowed the conventional capabilities leveraged in the initial, opening offensive and defensive operations. This overshadowing brings to question what level of resources should be directed toward assets typically thought of as conventional, both in form and function, like fighting vehicles. With major combat operations as the most dangerous course of action for the military, and with ground combat systems serving as an enabling asset in the prosecution of stability operations, fighting vehicle advancement and design remains an indispensable element in the creation and sustainment of combat power for future forces. Supporting this claim is the observation of vehicles pursued for stability purposes that have, over time, accumulated functional equipment to fill gaps in initially lacking attributes, such as survivability and lethality.

In analyzing the four quadrants of full spectrum operations, the basic properties and inherent capabilities of fighting vehicles seemed to be a vital asset in the prosecution of three types of full spectrum operations: offensive, defensive, and stability operations. Within these three types of operations, there is clearly a blending among types. For example, operations labeled nominally as offensive are characterized by some fraction of activity dedicated to both defensive and stability operations. In other words, even a sole focus on stability operations does not relax the requirement of U.S. forces to be capable of conducting offensive and defensive operations within the stability operation framework. In addition, this multifaceted prosecution of major combat operations reinforces the need for comprehensive fighting platforms that bring superior levels of firepower, protection, and mobility to bear on the enemy.

In reviewing the elements of combat power, a fighting vehicle's lethality, survivability, and mobility directly contributes to the protection, fires, and maneuver elements. As efficient and well-equipped energy transformers, combat platforms are significant elements in the generation of combat power, transforming potential power into combat actions conducive with the completion of offensive, defensive, and stability missions and related tasks. Finally, in analyzing the principles of war, the attributes afforded by a fighting vehicle's employment (presence and utilization) are complementary to at least five of the nine principles: offensive action, mass, maneuver, security, and surprise. This examination of the fundamentals reinforced the need for continued development on fighting vehicles that bring organic protection, firepower, and movement to the battlefield.

After revisiting the doctrinal basis for the utility afforded by a fighting vehicle and the enabling characteristics that make it a vital component of generating and sustaining combat power, a decision support framework was built around the principal attributes of survivability, lethality, and mobility. These chosen terms provide a doctrinally sound and technically founded basis in which to organize and classify engineering metrics.

In organizing the attributes, traits, and metrics that comprise the fighting vehicle domain, a metric crosswalk qualitatively demonstrated real competing demands between principal attributes. Most notably, the pursuit of higher survivability through conventional means can have penalizing effects on platform lethality and mobility. The mass and volume of improved survivability (via reducing vulnerability) worked against the objectives associated with better mobility, while also consuming weight and space that could be used for lethality-based equipment. Additionally, survivability even has conflicts among its own secondary traits. For example, the pursuit of reducing vulnerability through conventional means normally increases susceptibility. A large, heavy, well-fortified platform (low vulnerability) is typically, slow, cumbersome, and presents an easy target with distinct signature (high susceptibility). Equally important, invulnerable platforms are typically not mobile.

Parsing and discriminating the principal attributes at the three levels of war provided insight into the contrasting and complementary interests at specific stratum. Each level of war operates with its own, often fundamentally different, set of interests. While the tactical level is typically most concerned with possessing the greatest capability, the operational level is often most interested in the efficiency of such capabilities since this level is largely responsible for sustaining the intratheater combat power. The strategic level is primarily focused on the overall effectiveness of the network of warfighting elements.

The principal attributes were found to be well defined in both the literature and doctrine at the tactical level of war. Mobility, with its familiar analogs at the operational level (intratheater movement) and strategic level (intertheater movement or transportability) was also well defined at these two levels of war. But, for a tactical asset like a ground combat vehicle, the concept of lethality and survivability at the operational and strategic levels of war remains elusive and abstract. While the notion and connotation of these two attributes at the higher levels of war is appreciated at a superficial level, their refinement requires more analysis.

An exploratory thought experiment that considered the notional deployment of a ground combat vehicle in contact with a threat platform focused on the scaling of mass, length, and time of the principal attributes of survivability, lethality, and mobility at the tactical, operational, and strategic levels of war. This exercise demonstrated that the tactical level of war experiences the greatest range in mass, length, and time scales for combat actions related to survivability, lethality, and mobility. The operational and strategic levels enjoy greater stability and much narrower ranges of scale for these dimensional considerations. As fixed levels focused on generating and sustaining combat power, both spatially and temporally, the operational and strategic levels are largely isolated from the direct effects related to the operational uncertainty at the tactical level. Not surprising then, these two levels enjoy relative stability with respect to mass, length, and time scales associated with the principal attributes which demonstrates the inherent peril in designing a ground combat vehicle to largely meet the needs at the strategic and operational levels.

An additional exercise investigated the relative objective ranking of fielded combat platforms that demonstrated prowess; it indicated that strategic and operational mobility appear incongruent with tactical survivability and lethality. Platforms that possessed high levels of inter and intratheater transportability (i.e., good operational and strategic mobility) were typically not highly capable vehicles when measuring tactical lethality and survivability. The mass and volume associated with high levels of firepower and protection are not conducive with ease of movement at length scales commensurate with the operational and strategic levels of war. The benefit of rapid deployability (strategic mobility) is negated if the strategically positioned and operationally supported asset lacks the tactical lethality and survivability needed to perform its primary warfighting function of affording commanders and their crews with a mobile and protected weapon system.

6.4 Attribute Weighting and Candidate Vehicle Selection

The work in Chapter 3 demonstrated that decision support tools built around the principal attributes of survivability, lethality, and mobility can significantly improve the consistency of group selection of a ground combat vehicle. The improvements came from greater consistency between decision-maker attribute preference and the related levels of those attributes in candidate vehicles. Given that ground combat vehicles are primarily designed to be a mobile and protected source of firepower, it was logical to build an organizational framework around the principal attributes of survivability, lethality, and mobility, and then to place metrics appropriately beneath those attributes. As most decision support tools increase dimensions for candidate evaluation and rely on relative value comparisons, both techniques were employed in the comparison matrix creation and visual aids provided to respondents.

The abstraction of the desired qualities of a combat vehicle via principal attribute weighting can help steer engineering efforts and align programmatic interests with design work via "commander's intent" versus specifications. However, without insight as to the synergy and confliction among the principal attributes of survivability, lethality, and mobility, as well as a way to correlate those attributes with combat vehicle efficacy in a way representative of future mission profiles, the decision efficiency and consensus gained could be for naught. Stated more explicitly, an effort to quantify the effect an attribute has on combat vehicle performance should precede, rather than succeed, an attribute weighting solicitation.

A source of vulnerability in any decision making pursuit is the elusiveness of data to validate the decision quality. The inherent uncertainty in many pursuits, as well as the inability to forecast how alternative abandoned candidate selections may have fared, make it difficult to evaluate decision quality. In the absence of a definitive validation of weighting values, decision-maker and engineer can simply be consistently wrong in the pursuit of what is believed to be an effective combat vehicle. To use a marksmanship analogy, the tools used helped to "tighten the shot group" or reduce the difference between weighting-derived and overtly-chosen vehicle selection. However, a subsequent effort is necessary to see if the shots are "on target", i.e., is the candidate selection rank order validated by some simulation effort or practical demonstration exercise. Alternatively, a preceding effort aimed at investigating the relative value and parametric relationships between survivability, lethality, and mobility would do more to aid decision makers since information of this sort could contribute "further up stream" in the decision process. In other words, a deeper appreciation for the attribute interactions and correlations with platform performance could guide the creation of options as opposed to simply being used to choose better among a finite set of candidates. From a design perspective, insight gained on the relative contribution and interaction of each attribute might be used to direct performance metrics.

The U.S. Army officer survey respondents rated platform survivability as the most important principal attribute among survivability, lethality, and mobility. The concentration on survivability was likely reflective of a decade focused on stability operations, punctuated by increasingly lethal and sophisticated attacks with IEDs. The potential impact of pursuing attributes in an imbalanced fashion, especially when survivability can create debilitating performance penalties, has the potential to diminish fighting vehicle effectiveness, particularly in the conduct of major combat operations.

The combination of a priming exercise performed with a principal attribute weighting survey, along with a decision support tool explicitly designed to visualize data in accordance with those principal attributes, improved consistency in weightings and vehicle selection. The method of collapsing metric data beneath the principal attributes, and the visual depiction of the relative contribution to survivability, lethality, and mobility, was most preferred, but also potentially most misleading, among respondents.

It was mildly informative, but largely futile, to collect weighting data from such a robust population beyond the principal attribute level. In order to offer meaningful preferences on secondary traits, one must already possess deep insight as to the competing demands and dynamic interactions between combat vehicle sub-systems. At the metric level, weighting data was largely indistinguishable, their function would best be served with utility functions derived from engineering relationships.

A prerequisite for this effort was the collection of weighting data for the calculation and subsequent visualization of candidate vehicle performance specifications. Once the framework is established and the weighting values are accounted for, the amalgamation of performance specifications lends itself to any visual depiction consistent with the survivability, lethality, and mobility construct. Respondents had high preference for the bar-plot depiction of relative candidate levels of each principal attribute, and the use of this visual interpretation of performance data highly correlated to vehicle selection.

A source of vulnerability in any decision making pursuit is the elusiveness of validating the quality of the decision. The inherent uncertainty in many pursuits, as well as the inability to forecast how alternative candidate selections would have performed, makes it difficult to evaluate the quality of the decision. In the absence of a definitive validation, decision-maker and engineer may simply be consistently wrong in the pursuit of an ineffective combat vehicle.

6.5 Performance Effects and Attribute Interactions of Survivability, Lethality, and Mobility

With a basic framework enriched with synthesized weighting data from a representative population, the significance of these weightings with respect to platform performance was sought out in earnest. Using a DOE/ANOVA construct, in conjunction with a virtual reality combat simulation software tool, it may be possible to link platform performance with attribute efficacy. This methodology has the potential to address the single largest criticism of metric-based analysis, i.e., not connecting specification thresholds with platform performance. By designing and constructing virtual platforms in an orthogonal array with respect to varying levels of survivability, lethality, and mobility, and capturing system performance in a combat simulation exercise, the data demonstrated statistically significant attribute effects in conjunction with relative levels of protection, firepower, and movement.

Lethality appeared to be the dominating attribute, showing a statistically significant effect on performance for every *a posteriori* global metric (win %, blue %, red %, time %). Lethality was also the greatest source of cost for the platforms, both from the DOE/ANOVA data and the vehicle cost breakout study. Admittedly, given the relative simplicity of the simulation exercise, the one-on-one engagement with a peer threat on a battlefield absent of IEDs, friendly vehicles, and additional insult-producing systems, the scenario clearly favored greater firepower. As a participant in major combat operations or warfare typified by attrition, the ability to decisively destroy the threat led to greater mission success, faster mission completion, and greater survivability enabled by the eradication of the threat.

Mobility also had a positive effect on platform performance, albeit at a lower relative level and not always at a statistically distinguishable level. In the simulation exercise, greater mobility led to a change in tactics, where operators embraced a faster-paced, harassing fire and attack method. With enhanced lethality, operators largely focused on a more methodical, long-range engagement of the threat. This observation was evident in the results, where both lethality and mobility had a positive effect on every *a posteriori* performance metric.

Enhanced survivability had a negative effect on the performance of every candidate except the "triple plus" (enhanced survivability, lethality, and mobility). Survivability was also the greatest source of mass and volume for the platforms, both from the DOE/ANOVA data and the vehicle mass breakout study. As the vehicle became less vulnerable, through the assumption of more protective armor, the weight encumbered movement and reduced operator ability to maneuver the platform to a position of advantage necessary to destroy the target.

No statistically distinguishable attribute interactions were observed, but lethality and mobility clearly complemented each other in that both had commensurate levels of positive effect on performance. This matched the doctrinal definition of maneuver, or the use of fire and movement to dominate the enemy. And again, since the simulation operators appeared to embrace the benefits of either greater lethality or greater mobility by modifying offensive tactics, each attribute contributed to higher performance in a unique way. The effects of survivability and mobility were largely in line with expectation, but the results of increased lethality, even in this basic simulation package, were a surprise and demonstrated the value of including a human operator in the trigger-pulling portion of a simulation.

In the context of the simulation exercise, the mission operators performed slightly better on the wheeled variants versus the tracked candidates. This could have been due to increased proficiency (wheeled block followed tracked block of experiment) and general familiarity with wheeled vehicles. However, tracked vehicle performance included many more failures due to mission time-out (versus being destroyed by the threat platform).

6.6 Advanced Weapon System Concepts—Conventional Cannonry Versus Electromagnetic Guns

As the cornerstone for countless warfare simulation codes, the differential equations from the Lanchester Laws of Combat demonstrated that numerical superiority is overcome only by a large factor of dominance in system effectiveness. These laws shed light on the pursuit of higher effectiveness for conventional systems, as well as inform decision makers about the significance of the "quality versus quantity" debate. If one expects to fight as a numerical inferior, it is not sufficient to simply have overmatch against a foe. Rather, it appears to take large advances in system effectiveness to achieve the combat power necessary to create the conditions for success.

For a direct-fire, mobile cannon system, there are significant challenges associated with firing large projectiles at hypervelocity. Powder guns require increasingly larger propellant loads to achieve marginal increases in velocity. Railgun power supplies are very heavy and occupy too much space for a large-caliber tactical system. Considering an advanced, large-caliber cannon, it was deemed infeasible to pursue with existing technologies for either a powder gun or railgun. The large caliber hypervelocity powder cartridges are not conducive with a tactical platform magazine, and the power supply required for a large caliber railgun is too massive.

Even with these challenges, hypervelocity holds substantial benefit for both direct and indirect fire systems. These gains collectively generate greater effectiveness for an advanced concept direct fire weapon system, helping to further address the "quality versus quantity" issue. With respect to target effects, hypervelocity impact enjoys greater penetration efficiency than an ordnance velocity event. Additionally, the behind armor debris (BAD) is considerably greater for a hypervelocity projectile. In terms of engagement, hypervelocity reduces the time of flight between muzzle and target. For a constant energy system under fully developed, crosswind conditions, there is a minor increase in deflection at hypervelocity, correctable with proper sensing apparatus and an appropriate ballistic solution. At the source of commission (cannon) for a constant energy system, hypervelocity produces lower recoil force, thereby requiring less recoil mitigation equipment.

For a tank cannon (large caliber) concept, the 30+ MJ powder gun ammunition cartridge and barrel assembly becomes impractical for a hypervelocity concept. For a railgun design, while the integrated launch package and barrel design is quite compact, given current manufacturing technology and material properties, the power supply is infeasible with respect to both mass and volume. However, for an IFV cannon (medium caliber) concept, the 3 MJ IFV railgun system appears to be a feasible candidate. The railgun weapon system mass is four times that of a conventional system, but the ammunition is less than 25% as heavy and occupies much less space.

A power supply of this magnitude is also conveniently scaled to deploy an extended range mortar system. Mortars and IFVs can be considered the younger siblings of heavy artillery and main battle tanks, so the order of magnitude reduction in power supply requirements lends itself to conventional technologies. Additionally, the demand for heavy artillery and main battle tanks in stability operations is low, but the capabilities afforded by an electromagnetic direct fire and indirect fire family of platforms could provide substantial benefit to future warfighters. As previously discussed, the scaleable effects or option to tune the lethality of a weapon system is possible with railguns and could give commanders greater control in reducing collateral damage. At the other end of the spectrum, the lethality benefits created from firing at hypervelocity could yield great tactical advantage in terms of kinetic effectiveness.

Chapter 7: Future Work

In war, there is no second prize for the runner up.
—*General Omar Bradley*

So in the Libyan Fable it is told
That once an eagle, stricken with a dart,
Said when he saw the fashion of the shaft,
"With our own feathers, not by others' hands,
Are we now smitten."
—*Aeschulus*

7.1 Looking Forward

For the ground forces of the U.S. military, the decade following 9/11 could best be described as transformative. Stability operations, focused on engaging and defeating asymmetrical threats, while simultaneously providing security for rebuilding efforts, have dominated both theaters in Iraq and Afghanistan. Major combat operations, once the foundation for training and equipping ground forces, have clearly been superseded with counterinsurgency operations and the host of challenges associated with descriptive tasks, such as nation building, peace enforcement, and security training. At the same time, some peer competitor nations continue to pursue higher levels of performance in conventional systems for a range of reasons, including internal security, global ambitions, and export.

This presents a series of quandaries for the design and selection of the next generation of ground combat vehicles intended to replace legacy platforms like the M2 Bradley IFV. How should the successor platform requirements be drafted in order to pursue candidate vehicles conducive with battlefield dominance in future wars? And, given a set of valid requirements, what decision support tools can be leveraged to aid in the design and selection of an advanced fighting vehicle?

7.2 Ground Combat Vehicle Design Characteristics and Operational Considerations

If the doctrinal terms of survivability, lethality, and mobility adequately capture the imbued value and core functional requirements of a fighting vehicle on the battlefield, then the layering of these attributes at the three levels of war can help distinguish the relative merit of various technological pursuits at the various strata of military operations. There are areas of opportunity that may be worthy of further analysis and future work in this regard. Within the initial framework presented, which sought to introduce the concept of operational and strategic lethality and survivability, these previously undefined terms could benefit from more scrutiny and deeper analysis to determine what, if any, meaning can be assigned to them. At the tactical level, the principal attributes of survivability, lethality, and mobility were found to be well defined, both in doctrine and literature. Mobility at the operational and strategic levels was also clearly understood, since analogous terms like transportability and inter- and intratheater mobility are commonly used to describe the ability to move a combat vehicle at the higher echelons of command. However, while the terms of lethality and survivability may possess significance at the operational and strategic levels of war, these previously unexplored terms remain vaguely characterized. At best, a set of meaningful metrics was assigned to each in an effort to qualify, if not quantify, the significance of lethality and survivability at the operational and strategic levels of war. These terms are worthy of further analysis in both defining and quantifying their potential significance.

For a tactical asset, the concept of operational and strategic lethality and survivability remain ill defined and not yet fully understood. The concept of operational and strategic lethality simply does exist for weapon systems controlled at those respective levels. In addition, the exercises sought to create metrics describing the lethality and survivability considerations for a tactical asset at the operational and strategic levels as a way of conveying the essence of these previously unexplored terms. As a first look at these terms, more work should be done to create a better taxonomy and improved metrics that adequately serve a decision maker and facilitate easier use.

The proposed framework focused on the principal attributes deemed essential in the context of a study on fighting vehicles. In the materiel development world, large programs and projects typically focus on three global issues: cost, performance, and schedule. If the principal attributes presented in this manuscript revolve around the performance of the platform, then they could possibly be compressed into a performance branch, sharing that level with a further expansion of a cost and schedule branch. In other words, the first level in the hierarchal framework for the program decision support tool would begin with the cost, performance, and schedule branches.

For a ground combat vehicle, the survivability, lethality, and mobility framework could expand out from the performance branch. A complementary framework would need to be developed in order to add the cost and schedule branches. A large portion of this proposed work would fall under the purview of program management considerations, i.e., varieties in scheduling and cost considerations. The end state would be a decision support tool built around the ubiquitous programmatic considerations of cost, performance, and schedule.

It might also make for an interesting study to virtually deconstruct a complete legacy system, and account for the mass, volume, and financial cost associated with each component with a focus of accounting for the explicit or implicit contribution of each with respect to survivability, lethality, and mobility. For example, consider a bare turret and hull for an Abrams tank. With the cost, mass, and volume occupied by each of these major components, some fraction of each would contribute (objectively and/or subjectively) to the platform survivability, lethality, and mobility. As one virtually built the vehicle via the military logistics system, data on the weight, volume, and cost of each part and component could be sorted and fractioned among the principal attributes accordingly. Once complete, the investigator would have a breakout of how the fighting vehicle's mass, volume, and cost are apportioned among the principal attributes comprising the combat system efficacy. This could provide a historical reference as to how weight, volume, and cost were apportioned among the various systems comprising a combat vehicle, as well as provide insight as to how one might best pursue a reduction in weight, volume, or cost by addressing the most prevalent attribute in a respective area of concern.

This was done at a very small scale using the JRATS platforms and design information provided as components. A preliminary effort, approximating 25% of the vehicle hull and mobility components, was also done using an M1A2 Abrams and the logistic database provided by the logistics supply agency (LOGSA). Knowledge and expertise of the end item (vehicle) is required to efficiently order the major systems and subsystems in order to avoid deconstructing the vehicle down into too small of parts. Additionally, some components will objectively contribute to a principal attribute (e.g., the track serves the platform principal attribute of mobility), while others will subjectively divide among attributes. For example, some fraction of the hull mass, cost, and volume contribute to platform mobility, with the residual supporting survivability and lethality considerations. With some level of uncertainty and interpretation, an effort such as this should depict where the mass, cost, and volume were consumed with respect to the principal attributes of survivability, lethality, and mobility.

7.3 Performance Effects and Attribute Interactions of Survivability, Lethality, and Mobility

The JRATS software served as an exploratory effort in identifying the competing demands and complementary relationships between survivability, lethality, and mobility. As a single-user system fighting against a basic threat platform, it had the basic requirements to conduct the described study. This technique could be applied to leverage the much more sophisticated combat simulation environments at the U.S. Army's disposal. Considerable up-front work would have to be done in order to tune existing simulated capabilities in a way conducive with the DOE construct. However, these simulations are far superior in realism and user interaction than the JRATS title. The close-combat-tactical-trainer (CCTT) comes to mind as a candidate system. CCTT is largely used to teach mounted maneuver warfare in a simulated environment. In the CCTT, crews work together in a realistic capsule representing the interior of a fighting vehicle.

Systems are networked together and visible through viewing ports and periscopes, providing the ability to fight as a combined arms team. In the context of DOE, a framework designed around the principal attributes of survivability, lethality, and mobility, could conceivably be tuned up and down in order to replicate the two-level, three-factorial candidate vehicle design used in this study. CCTT end state metrics would be recorded to further explore the effects and interactions of these principal attributes on fighting vehicle performance. As mentioned in Chapter 4, the dynamics and interplay between systems with regard to lethality places great value on the inclusion of a human in the decision making cycle of commission of a lethal, albeit simulated, munition.

In this experiment, the statistics were designed to analyze the correlation of performance with respect to the attributes of interest (survivability, lethality, and mobility), so a subsequent study would have to be conducted to pursue the sensitivity of user performance to candidate design. Finally, in accordance with full spectrum operations, future simulations should include both defensive and stability operations to evaluate ground combat performance and the relative contribution of principal attributes in a broader mission profile.

For the classical decision analysis portion of this manuscript, the apparent shortcomings of AHP suggest further investigation of MAUT. A hybridization effort that uses MAUT for the initial direction for an advanced technology pursuit, followed by an AHP effort to guide the final aspects of a project, might be beneficial. Nanry's *Econometric Frontier Analysis* uses an MAUT approach for the decision analysis with respect to pursuing high risk, but high reward, military technologies. The proposed hybrid approach would be consistent with this technique.

When considering the DOE methodology, the principal attributes were tested at the tactical level. In addition to a more robust platform and integration of multiple systems, the attributes could be expanded to the three levels of war, making for a two-level, 9-factorial experiment. This might illuminate in a quantitative fashion the inherent conflicts and synergisms between the principal attributes at the levels of war. Additionally, the performance metrics could be collapsed and a similar study using the DOE framework could be done in order to explore the relationships between cost, performance, and schedule. This was done in observation only in Chapter 4, since the DOE test matrix was designed around the principal attributes, and particularly not cost, performance and schedule effects, i.e., enhanced and acceptable levels of cost and schedule.

Related to the DOE experiments done in Chapter 4, the missions consisted solely of offensive operations against a peer threat. In order to fully explore the contributions of a ground combat vehicle in full spectrum operations, further study could include defensive, as well as stability operations, for single as well as multiple systems. If a decision maker had a sense for the future operational demand tendencies, i.e., stability focused, the results could provide the relative effects and interactions among attributes toward the performance metrics of interest in that particular type of full spectrum operations. Finally, any future DOE work involving users actively fighting virtual systems in a simulated combat environment should include user sensitivity analysis. This might reaffirm the need to pursue revolutionary, versus evolutionary, improvements in an attribute since marginal increases may not be significant enough to be statistically distinguishable given the operators' proclivity to adopt to and adapt with the platform they are given.

7.4 Advanced Weapon System Concepts—Conventional Cannonry Versus Electromagnetic Guns

Since survivability, as an attribute, presented such penalty to the other attributes—both conceptually in Chapter 2 and in simulated results in Chapter 4—this clearly represents an area requiring a revolutionary technology development. Simply adding more armor to reduce vulnerability is an exercise bound to increase susceptibility and reduce mobility and lethality. Likewise, if the U.S. Army continues to fight off a charter based on major combat operations, it appeared from the simulation exercise that lethality was the attribute that produces the greatest effect on key performance metrics like win %. For railguns and other weapons associated with electric fires, this will require further work in power supply and switching technology. As previously discussed, in the 225 year history of the U.S. Army, there has been active participation in only 11 major wars, but hundreds, if not thousands, of actions described as dealing with stability operations. The future descriptor of this class of operation has been referred to as wide-area security missions (WASM). Observations of ongoing operations in Afghanistan depict a WASM, i.e., small units widely dispersed, conducting missions in support of stability operations.

With the focus on WASM, indirect-fire coverage at a theater level could be a desirable capability of the operational, as well as tactical, level commanders in the area of operations. For a theater of the size representative in Afghanistan, 3 strategically placed 100+MJ railguns could provide indirect coverage of forward operating bases and combat outposts. A system of this scale would match the U.S. Navy's railgun program, and provide a first-look for ground forces as to the tactical, operational, and strategic implications of introducing a revolutionary weapon technology on the battlefield.

Furthermore, the pursuit of a static, ground-based, theater-level railgun system would relax the spatial and mass requirements that currently make this technology infeasible for a mobile system. Finally, the continued development of ground-based railgun systems could promote further development in an emerging area of technological innovation that several peer threat countries have deemed as being nothing less than the next generation of warfare. The minimal cost of, at least, sustaining the current level of understanding, and more importantly, preserving the human capital that have fostered development in electromagnetic launch, could far outweigh the risks of abandoning a technology which, if matured, would expand the performance capabilities for direct- and indirect-fire weapons far beyond what is achievable with conventional technology.

7.5 Putting the "Mechanical Turk" to Work for the U.S. Army

A shared goal of both DARPA's AVM/FANG and the U.S. Army's GCV programs is the pursuit of greater assured success in the form, fit, and function of initial prototypes, enabled by higher fidelity, multi-physics modeling and simulation efforts during the virtual design of vehicle concepts. Consistent with the goal of eliminating/minimizing the number of physical prototypes that are required, a Mechanical-Turk-like virtual battlefield can be developed to allow U.S. Army personnel to virtually fight and simultaneously collect mission-related performance data that can provide an in-stride assessment of the ongoing design efforts. This concept was inspired by Amazon's *Mechanical Turk*, in which humans perform tasks via an online interface that machines cannot yet do as efficiently or effectively.[262] For example, an online publisher might ask participants to write a short book synopsis, and in reward, will pay some nominal fee for each synopsis, i.e., task performed. As conceived here, engineers would continue to improve their design prototypes, which would be available continuously (and updated as appropriate) for virtual combat by a set of operators that could test the vehicles in a combat environment typical of current and future anticipated theaters of battle. For example, virtual crews can register for access to the environment. After signing in and receiving a simulated mission brief, they can fight the platforms (commanders, gunners, drivers, etc.); simultaneously and transparent to the user, performance of the vehicle variants as well as that of the operators is collected for subsequent analysis and synthesis to assess the relative merits (or demerits) of any design modifications. In this way, the sensitivity of the design specifications with respect to simulated combat vehicle performance, as well as the relative effect of pursuits in

[262] Duncan J. Watts, *Everything Is Obvious: Once You Know The Answer* (New York: Crown Business, 2011) 190-196, 209.

enhancements (similar to that in Chapter 4) can provide valuable, real-time feedback to designers and program managers alike.

During periods of urgently needed redesign, the networked operators and threat environment can be virtually imported to the actual operational theater through existing frameworks used for mission rehearsal exercises (MRE). Here again, designer and manager can provide in-stride feedback on the design through the evolution of the quest for a successor vehicle or modification to a legacy system, as opposed to the current practice of assessing design efficacy less frequently and without the immense knowledge base that a virtual simulation environment provides.

A U.S. Army version of the *Mechanical Turk* that provides an iterative, integrated design-assessment means for fighting vehicle design represents a significant paradigm shift in the pursuit of an advanced ground combat vehicle. It embraces a *searcher*—rather than *planner*—approach, one not coincidently paralleling the *mystery* and *puzzle* paradigm. This methodology relies on performance data to direct and proactively influence the design effort, versus relying on engineering specifications to forecast the ability to achieve superior system performance. While one might anticipate some initial resistance or reluctance to adopt this paradigm, the benefit it offers could be great. Rewards of pursuing attribute enhancements, e.g., survivability, lethality, or mobility, as a function of simulated fighting vehicle operational performance should outweigh the risk and complexity associated with crowd sourcing as well as “freeing” and “democratizing” the design effort in a way not seen before in the development of a fighting vehicle.

Appendices

Appendix 1: Technology Readiness Levels (TRLs) and Definitions.

The following matrix lists the various technology readiness levels and descriptions from a systems approach for both hardware and software.[263]

Technology Readiness Level (TRL)	**TRL Description**
1. Basic principles observed and reported.	Low level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated. Invention begins.	Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic (paper) studies.
3. Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "levels of war fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5. Component and/or breadboard validation in relevant environment. .	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.

[263] Virtual Acquisition Handbook for Program Executive Office Combat Support and Combat Service Support (PEO CSCSS), Tank-Automotive and Armaments Command (TACOM), Warren, Michigan, 2010.

Appendix 1 (continued)

Technology Readiness Level (TRL)	TRL Description
6. System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
7. System prototype demonstration in an operational environment	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in structured or actual field use.
8. Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected operational conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended or preproduction configuration to determine if it meets design specifications and operational suitability.
9. Actual system proven through successful mission operations.	Actual application of the technology in its production configuration and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system by operational users under operational mission conditions.

Appendix 1 (continued)

Supplemental definitions

Breadboard: Integrated components that provide a representation of a system/subsystem and which can be used to determine concept feasibility and to develop technical data. Typically configured for laboratory use to demonstrate the technical principles of immediate interest. May resemble final system/subsystem in function only.

High Fidelity: Addresses form, fit and function. High-fidelity laboratory environment would involve testing with equipment that can simulate and validate all system specifications within a laboratory setting.

Low Fidelity: A representative of the component or system that has limited ability to provide anything but first order information about the end product. Low-fidelity assessments are used to provide trend analysis.

Model: A functional form of a system, generally reduced in scale, near or at operational specification. Models will be sufficiently hardened to allow demonstration of the technical and operational capabilities required of the final system.

Operational Environment: Environment that addresses all of the operational requirements and specifications required of the final system to include platform/packaging.

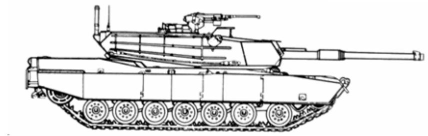
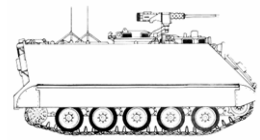
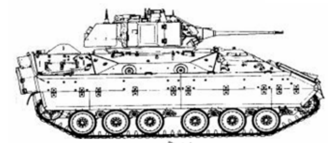
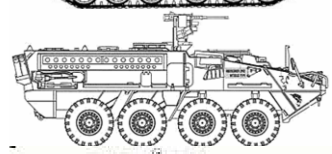
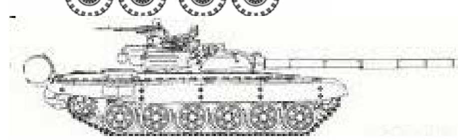
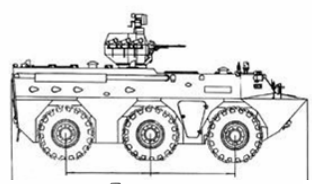
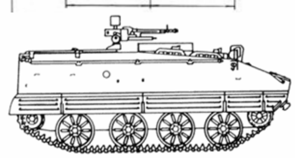
Prototype: A physical or virtual model used to evaluate the technical or manufacturing feasibility or military utility of a particular technology or process, concept, end item or system.

Appendix 1 (continued)

Relevant Environment: Testing environment that simulates the key aspects of the operational environment.

Simulated Operational Environment: Either 1) a real environment that can simulate all of the operational requirements and specifications required of the final system, or 2) a simulated environment that allows for testing of a virtual prototype; used in either case to determine whether a developmental system meets the operational requirements and specifications of the final system.

Appendix 2: Countries of Origin and Side View Drawings for Combat Vehicle Set[264]

BMP-3	Russian	
M1A1	U.S.	
M113	U.S.	
M2A2	U.S.	
Stryker	U.S.	
T-72	Russian	
WZ551	Chinese	
YW531	Chinese	

[264] Christopher F. Foss, Jane’s Armor and Artillery, 2006-2007. Virginia: Cambridge University Press, 2006.

Appendix 3: Research Proposal for the University of Texas Human Subject Institutional Review Board (IRB).

IRB Research Proposal
Joshua M. Keena
PhD Candidate, Mechanical Engineering
University of Texas at Austin

I. Title: Attribute Weighting Survey Questionnaire for Ground Combat Vehicle Design and Selection Considerations

II. Investigators (co-investigators): Joshua M. Keena

III. Hypothesis, Research Questions, or Goals of the Project: The goal of this project is to capture the subjective relative weightings soldiers place on the multitude of attributes and metrics used to design and select ground combat vehicles.

IV. Background and Significance:

The design and/or selection of a ground combat vehicle is often an exercise in trade-offs enabled by appropriate decision support tools. In order to aid in the compilation and distillation of performance data, measurable attributes are often weighted appropriately (Saaty, 1977). By querying a statistical sample of the user population with questions focused on capturing the subjective weightings each places on the various performance aspects of a ground combat vehicle candidate, these weightings can subsequently be used to either guide design efforts and resources or to streamline selection processes.

V. Research Method, Design, and Proposed Statistical Analysis:

I will present the participants with a series of ground combat vehicle attributes and metrics organized in accordance with a hierarchy. The participants will first be asked to rank order the attributes, and subsequently they will be asked to subjectively rate the attributes with respect to the predecessor. The goal of this second step is to use the weightings with a pair-wise rating algorithm (Hwang and Yoon, 1983). A consistency ratio check will be performed on the weightings prior to analysis. The collected data will be analyzed with respect to standard deviation, mean, and median. Attribute weightings will then be applied to the various metrics in the framework of a decision support tool being constructed.

VI. Human Subject Interactions

A. The potential participants will be active Army soldiers attending the Institute for Advanced Technology's (IAT) Intermediate Qualification Course (IQC). This three-week course, hosted by the IAT, is focused on providing Acquisition Corps (AC) officers with procurement field training. The population will be both male and female Soldiers, aged approximately from 30-45. The total population of

B. participants will number approximately 60 subjects. In accordance with Army regulations and standards, all participants will be in good health. Given the fact that the population will be composed of more senior (field grade) military officers, it is highly unlikely that any of the participants are likely to be vulnerable to coercion or undue influence. All students enrolled in the IQC course meet screening criteria and are eligible for inclusion in the study. Participation will of course be voluntary, and there will be an alternate activity available for those not wishing to contribute to this research project. I expect human subject involvement in this project to begin in late October, 2010 and to end in late March 2011.

B. The course director for the IQC program of instruction (POI) has agreed to allow me to use 75 minutes of discretionary time in his course to conduct this survey questionnaire. Students formally enrolled in the IQC course through the Army Training Requirements and Resource System (ATRRS) have been prescreened and are fully qualified, both professionally and academically, to participate in this study.

C. I will present all participants with a consent form and maintain copies with my confidential research archives. Additionally, each participant will be given a copy of the signed consent form.

D. **Research Protocol**. I will ask participants to rank and weight various ground combat vehicle performance metrics and attributes. They will fill out the questionnaire in the conference room of the IAT during a discretionary period in the IQC syllabus. It should take 60 minutes to fill out the survey, and I have been allotted an additional 15 minutes for a brief introduction period as well as questions and answers. The data collected on each participant will be what is known in the Army as a standard name line (SNL), as well as three pieces of data used for professional background cataloging. This will include combat experience, graduate education, and current job position.

E. I will protect and observe the privacy of each participant by only contacting them with follow up questions using methods they have agreed to on the questionnaire. Furthermore, I will contact them during times that they have indicated are acceptable (e.g., a professional email account 'army knowledge online' or 'ako').

F. I will protect the confidentiality of participants by maintaining strict control of all questionnaires in a locked file cabinet maintained in my office at the IAT, room 4.11126. I will not divulge to others any data that is inconsistent with the understanding of the original disclosure. The names will only be recorded on the original survey. All digital entries and subsequent analysis will rely on a code generated for confidentiality purposes. I will destroy this data within 12 months, no later than August 31, 2011.

G. The IQC coordinator has afforded me access to the course population during a period of discretionary time. We will conduct the survey in an established conference room.

VII. I rate this survey exercise as low risk. If, for unforeseen circumstances, I lose confidentiality of the participants' responses, I will notify the participants of this through established contact methods.

VIII. The participants could benefit from contributing to this project because they will be exposed to an organizational framework for cataloging and weighting the various principal and derivative metrics used to quantify the relative merit of a ground combat system. Since the participants are all serve in the military procurement field, this subject is apropos for the range of specialists I anticipate engaging with. The benefits of participation heavily outweigh the risks.

IX. No other sites or agencies are involved in this research project.

X. This project will not receive review from another IRB.

Respectfully,
Joshua M. Keena
PhD candidate

Appendix 4: IRB Consent Form

Title: *Attribute Weighting Survey Questionnaire for Ground Combat Vehicle Design and Selection Considerations*
IRB PROTOCOL #
Conducted By: Joshua M. Keena
Of The University of Texas at Austin: *Department / Office*; ME/4.11126 Telephone: 232-4471

You are being asked to participate in a research study. This form provides you with information about the study. The person in charge of this research will also describe this study to you and answer all of your questions. Please read the information below and ask any questions you might have before deciding whether or not to take part. Your participation is entirely voluntary. You can refuse to participate or stop participating at any time without penalty or loss of benefits to which you are otherwise entitled. You can stop your participation at any time and your refusal will not impact current or future relationships with UT Austin or participating sites. To do so simply tell the researcher you wish to stop participation. The researcher will provide you with a copy of this consent for your records.

The purpose of this study is to capture the subjective relative weightings soldiers place on the multitude of attributes and metrics used to design and select ground combat vehicles. I intend to interview up to 60 soldiers for this study.

If you agree to be in this study, we will ask you to do the following things:

- Participants will be oriented to the research project through a short presentation
- Participants will be given a short descriptive vignette of the design considerations for a future ground combat vehicle
- Participants will be asked to rank order, then subjectively rate, a collection of attributes and metrics descriptive of the measurable aspects of a vehicle

Total estimated time to participate in study is 75 minutes

Risks of being in the study are no greater than everyday life.

Benefits of being in the study include exposure to the design process and requisite considerations for trade off analysis with respect to ground combat vehicles.

Compensation: none

Confidentiality and Privacy Protections:
The data resulting from your participation may be made available to other researchers in the future for research purposes not detailed within this consent form. In these cases, the data will contain no identifying information that could associate you with it, or with your participation in any study.

The records of this study will be stored securely and kept confidential. Authorized persons from The University of Texas at Austin, members of the Institutional Review Board, and (study sponsors, if any) have the legal right to review your research records and will protect the confidentiality of those records to the extent permitted by law. All publications will exclude any information that will make it possible to identify you as a subject. Throughout the study, the researchers will notify you of new information that may become available and that might affect your decision to remain in the study.

Contacts and Questions:

If you have any questions about the study please ask now. If you have questions later, want additional information, or wish to withdraw your participation call the researchers conducting the study. Their names, phone numbers, and e-mail addresses are at the top of this page.

If you would like to obtain information about the research study, have questions, concerns, complaints or wish to discuss problems about a research study with someone unaffiliated with the study, please contact the IRB Office at (512) 471-8871 or Jody Jensen, Ph.D., Chair, The University of Texas at Austin Institutional Review Board for the Protection of Human Subjects at (512) 232-2685. Anonymity, if desired, will be protected to the extent possible. As an alternative method of contact, an email may be sent to orsc@uts.cc.utexas.edu or a letter sent to IRB Administrator, P.O. Box 7426, Mail Code A 3200, Austin, TX 78713.

You will be given a copy of this information to keep for your records.

Personal Data

Name: ____

Age:________ Gender:_________ Basic Branch / MOS: _________

Highest degree attained (e.g. AA, BS):_____________

Operational Experience: ____
(e.g. SFOR, OEF, include # of tours for multiple deployments)

Current Duty Position and
Organization:____

Appendix 5: Attribute Weighting Survey Script

Attribute Weighting Survey Script

In support of the construction of a decision support tool being used in both the design and selection of the next Ground Combat Vehicle (GCV) candidate, you have been asked to provide your objective and subjective input for the generation of attribute weighting values. At this early stage, consider the GCV as the successor to the Bradley Infantry Fighting Vehicle (M2A3 IFV). Your contribution to this study should be a reflection of your past military experiences, present duty position, and, perhaps toughest of all to predict, what you foresee to be the needs and capabilities of our future armed forces. Undoubtedly, the potential combat scenarios for future warfighters include a mix of both conventional (e.g. Desert Storm) and irregular warfare (e.g. OIF, OEF).

In the context of this exercise, you are going to focus strictly on combat platform performance. Cost and schedule considerations are being addressed in a subsequent forum. Moreover, with respect to performance, consider the worth of a ground combat vehicle to be a function of its principal attributes of Lethality, Survivability and Mobility. These three principal attributes can be further broken down into secondary traits and tertiary metrics.

While the GCV is clearly a platform that will operate as a tactical level asset, one should also consider the operational and strategic implications of the principal metrics. Some of these are easy to conceptualize (e.g. Strategic Mobility, like intertheater transportability), and others are more abstract notions (e.g. Operational Lethality, like collateral damage incurred). For tactical assets, it is normally easier to envision the negative operational and strategic implications of the principal attributes. In any case, use your best judgment when providing your rankings and feedback.

Appendix 6: Attribute Weighting Survey Tool

Part I: Introduction

In support of the construction of a decision support tool being used in both the design and selection of the next Ground Combat Vehicle (GCV) candidate, you have been asked to provide your objective and subjective input for the generation of attribute weighting values. At this early stage, consider the GCV as the successor to the Bradley Infantry Fighting Vehicle (M2A3 IFV). Your contribution to this study should be a reflection of your past military experiences, present duty position, and, perhaps toughest of all to predict, what you foresee to be the needs and capabilities of our future armed forces. Undoubtedly, the potential combat scenarios for future warfighters include a mix of both conventional (e.g. Desert Storm) and irregular warfare (e.g. OIF, OEF).

In the context of this exercise, you are going to focus strictly on combat platform performance. Cost and schedule considerations are being addressed in a subsequent forum. Moreover, with respect to performance, consider the worth of a ground combat vehicle to be a function of its principal attributes of Lethality, Survivability and Mobility. These three principal attributes can be further broken down into secondary traits and tertiary metrics.

While the GCV is clearly a platform that will operate as a tactical level asset, one should also consider the operational and strategic implications of the principal metrics. Some of these are easy to conceptualize (e.g. Strategic Mobility, like intertheater transportability), and others are more abstract notions (e.g. Operational Lethality, like collateral damage incurred). For tactical assets, it is normally easier to envision the negative operational and strategic implications of the principal attributes. In any case, use your best judgment when providing your rankings and feedback.

Appendix 6 (continued)

Part II: Principal Attributes at the 3 Levels of War

Working definitions:

Lethality is defined as the probability that a weapon will damage or destroy a target such that it can no longer carry out its intended mission.

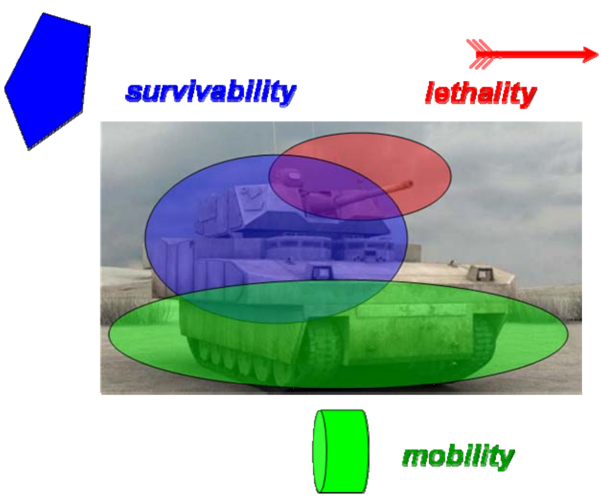
Mobility is defined as a quality of a combat platform which permits movement from place to place while retaining the ability to fulfill its primary mission.

Survivability is defined as an inherent quality of protecting personnel, weapon system, and equipment such that the crew can carry out their dedicated mission.

The **Strategic** level of war is the level at which a nation determines security objectives and guidance, and develops and uses national resources to achieve these objectives.

The **Operational** level of war links the employment of tactical forces and flow of sustenance resources to achieve the strategic end state.

The **Tactical** level of war is the employment and ordered arrangement of forces using combat power to accomplish missions.



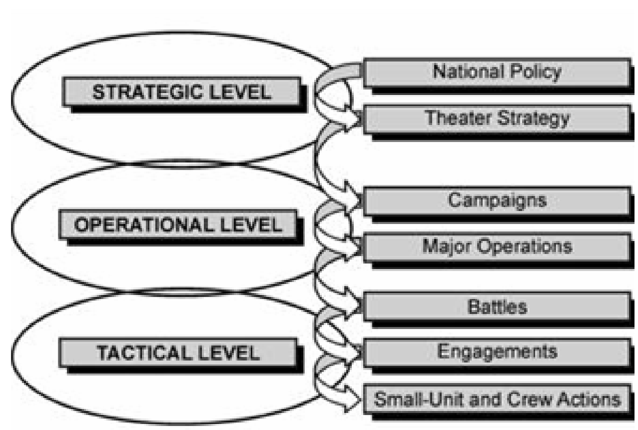


Figure 1 (left): GCV virtual prototype with highlighted regions contributing to attributes of lethality, mobility, and survivability.
Figure 2 (right): Levels of War.

Appendix 6 (continued)

Considering the GCV concept, rank order the principal attributes of Lethality, Mobility, and Survivability as you value their relative importance to the overall performance of the vehicle.

1.______________________________

2.______________________________

3.______________________________

With respect to #2, #1 is: Equal Slightly favored Favored Strongly favored
(circle one)
With respect to #3, #1 is: Equal Slightly favored Favored Strongly favored
(circle one)
With respect to #3, #2 is: Equal Slightly favored Favored Strongly favored
(circle one)

Rank order, from 1-9, with 1 being the most important to you, and 9 being the least important to you, a ground combat system's attribute characteristics of Lethality, Mobility, and Survivability at the three levels of war, i.e. (Tactical Lethality, Operational Lethality… Strategic Survivability).

Level and attribute	(rank)
1. Tactical Lethality	_________
2. Tactical Mobility	_________
3. Tactical Survivability	_________
4. Operational Lethality	_________
5. Operational Mobility	_________
6. Operational Survivability	_________
7. Strategic Lethality	_________
8. Strategic Mobility	_________
9. Strategic Survivability	_________

Appendix 6 (continued)

Part III: Lethality

Considering the definition for lethality, this attribute is a function of the weapon system capacity to acquire and deploy a payload (Acquisition), the ability to fly from muzzle to target (Engagement), and the effects generated on the target (Effects).

Rank order the secondary traits of Lethality, namely Acquisition, Engagement, and Effects as you value their relative importance to the performance of the vehicle.

1.______________________________

2.______________________________

3.______________________________

With respect to #2, #1 is: Equal Slightly favored Favored Strongly favored
(circle one)
With respect to #3, #1 is: Equal Slightly favored Favored Strongly favored
(circle one)
With respect to #3, #2 is: Equal Slightly favored Favored Strongly favored
(circle one)

The following is a list of metrics that relate to the Lethality of a weapon system. Based on your experience and knowledge, these metrics may vary from familiar (e.g. range) to unfamiliar (e.g. BAD or behind armor debris). In any case, please rank the following metrics from 1 (most important) to 10 (least important).

Metric	Rank	Short Definition
BAD	______	behind armor debris, material flying behind target
CAL	______	combat ammunition load, rounds stored on platform
F_{recoil}	______	recoil force after firing, weapon system kick
KE	______	kinetic energy imparted to target
l_{cannon}	______	cannon length
MER	______	maximum effective range, how far can you hit a target
P_{kill}	______	probability (percent chance) that target is killed
t_{flight}	______	time of flight to target
t_{reload}	______	time to reload weapon
tuneability	______	ability to tune or scale weapon effect to target specificity

List one additional metric you would want to consider with respect to Lethality:

Appendix 6 (continued)

Part IV: Mobility

Considering the definition for mobility, this attribute is a function of the platform capability to drive on unimproved surfaces (Cross Country), the ability to move on improved surfaces (Roadworthiness), and the capacity for which it can deal with the unforeseen manmade and natural obstacles it may encounter (Robustness).

Rank order the secondary traits of Mobility, namely Cross Country, Roadworthiness, and Robustness as you value their relative importance to the performance of the vehicle.

1.______________________________

2.______________________________

3.______________________________

With respect to #2, #1 is: Equal Slightly favored Favored Strongly favored (circle one)

With respect to #3, #1 is: Equal Slightly favored Favored Strongly favored (circle one)

With respect to #3, #2 is: Equal Slightly favored Favored Strongly favored (circle one)

The following is a list of metrics that relate to the Mobility of a combat platform. Based on your experience and knowledge, these metrics may vary from quite familiar (e.g. v_{max}, or top speed) to unfamiliar (e.g. P/w ratio or the ratio of engine power to vehicle weight). In any case, please rank the following metrics from 1 (most important) to 10 (least important).

Metric	Rank	Short Definition
CG	_____	height of center of gravity, measure of stability
h_{climb}	_____	vertical height of obstacle that vehicle can climb over
P/w	_____	ratio of engine power to gross vehicle weight
range	_____	range vehicle can travel without resupply
r_{turn}	_____	turning radius
VCI_n	_____	vehicle cone index, measure of ability to travel on soil
v_{max}	_____	maximum velocity or top speed
w_{gap}	_____	width of gap that vehicle can cross over
η_{fuel}	_____	fuel efficiency
$\%_{slope}$	_____	percent slope that vehicle can climb

List one additional metric you would want to consider with respect to Mobility:

Appendix 6 (continued)

Part V: Survivability

Considering the definition for survivability, this attribute is a function of the platform capacity for which it can recover from damage (Repairability), the ability to avoid detection (Susceptibility), and the ability to take a hit (Vulnerability).

Rank order the secondary traits of Survivability, namely Repairability, Susceptibility, and Vulnerability as you value their relative importance to the performance of the vehicle.

1.______________________________

2.______________________________

3.______________________________

With respect to #2, #1 is: Equal Slightly favored Favored Strongly favored
(circle one)
With respect to #3, #1 is: Equal Slightly favored Favored Strongly favored
(circle one)
With respect to #3, #2 is: Equal Slightly favored Favored Strongly favored
(circle one)

The following is a list of metrics that relate to the Survivability of a combat platform. Based on your experience and knowledge, these metrics may range from quite familiar (e.g. mass or weight of the vehicle) to unfamiliar (RHA_{eq} or equivalent armor thickness). In any case, please rank the following metrics from 1 (most important) to 10 (least important).

Metric	Rank	Short Definition
A_{cross}	______	cross sectional area or silhouette presented to threat
$A_{footprint}$	______	footprint area occupied by platform
BPR	______	blast protection rating, akin to the yield of an IED
$E_{combustible}$	______	combustible or flammable energy stored on board
e_m	______	areal density ratio of armor with respect to rolled steel
$h_{clearance}$	______	ground clearance of vehicle
mass	______	gross vehicle mass or weight
modularity	______	number of main sub-components comprised of vehicle
RHA_{eq}	______	armor thickness, equivalent with respect to rolled steel
v-hull	______	belly of vehicle has vee shape

List one additional metric you would want to consider with respect to Survivability:

Appendix 6 (continued)

Part VI: Decision Support Tools

After an exhaustive design and analysis process comprising several years, you have now been asked to participate in the selection of the next GCV. A brief summary of the respective performance is listed below. This is only raw data, i.e. weights and relative scores have not been computed yet as you would see on a decision matrix.

Table 1

Metrics ► Candidate ▼	P_{kill} prob. of kill [%]	KE kinetic energy [MJ]	MER max eff range [m]	v_{max} max speed [km/hr]	r range [km]	P/w power to weight [kW/ tonne]	RHA_{eq} armor thickness [mm]	BPR blast rating [kg yield]	$E_{comb.}$ on board fuel [MJ]
A	95	12	4000	66	300	11	850	300	80,000
B	70	6	2500	100	500	16	600	250	60,000
C	65	5	3200	45	250	12	1000	500	50,000

You may notice that the first three metrics deal with lethality, the next three address mobility, and the last three focus on survivability. With respect to the current inventory of Army vehicles, if one were to nondimensionalize the performance values for the three principal attributes by dividing the value by an established, familiar standard, the Abrams main battle tank, Stryker armored personnel carrier, and MRAP mine resistant utility vehicle could serve as the respective benchmarks. For example, instead of considering a vehicles range in kilometers or miles, if its nondimensional range was greater than 1, it would be better than the Stryker, if it were less than 1, it would be worse than the Stryker, and if it were equal to 1, it would be equal to the Stryker.

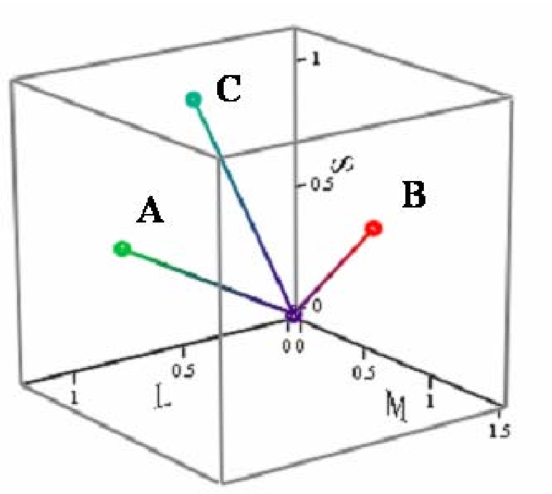
Following this normalization effort using the Abrams, Stryker, and MRAP as the standard of performance for lethality, mobility, and survivability metrics respectively, the data in table 1 has been nondimensionalized and is displayed in table 2 below.

Table 2

Metrics ► Candidate ▼	P_{kill}	KE	MER	v_{max}	r	P/w	RHA_{eq}	BPR	$E_{comb.}$
A	1.10	1.12	1.25	0.65	0.60	0.69	0.85	0.67	1.21
B	0.72	0.61	0.64	1.08	1.14	1.04	0.61	0.55	1.44

Appendix 6 (continued)

Additionally, this nondimensionalized data can be depicted graphically. For example, the three candidates A,B, and C, can be plotted on axes representing relative lethality, mobility, and survivability with respect to the aforementioned benchmarks.



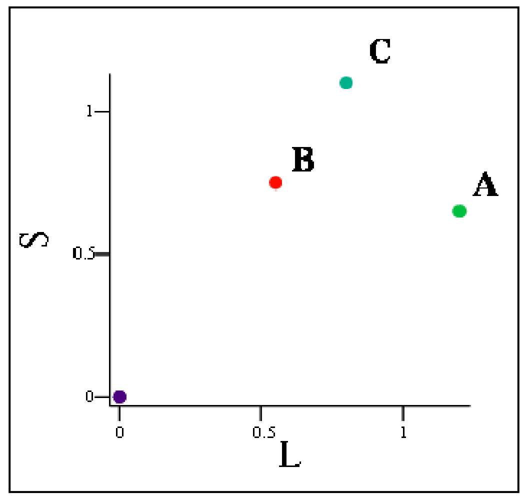
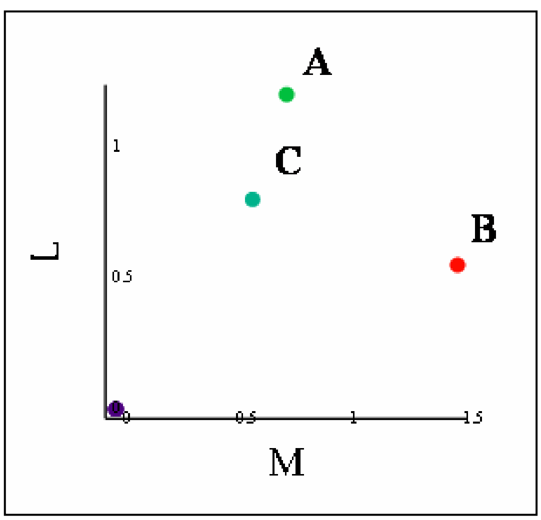


Figure 3 (left): plot of candidates A,B, and C on x-y-z axis of Lethality, Mobility, and Survivability
Figure 4 (right): plot of Survivability versus Lethality for candidates A,B, and C



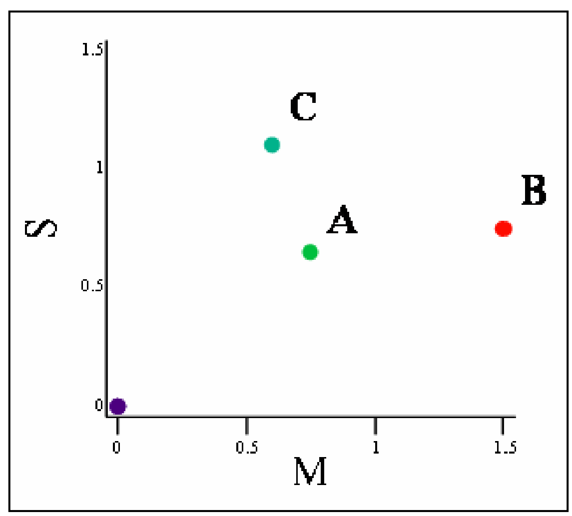


Figure 5 (left):): plot of Lethality versus Mobility for candidates A,B, and C
Figure 6 (right): plot of Survivability versus Mobility for candidates A,B, and C

Appendix 6 (continued)

If you were choosing a GCV candidate, please rank order the tables and figures that would be most helpful in making a selection. As a reminder:

- Table 1 is raw data that you would encounter in a standard decision matrix
- Table 2 is the same data normalized against established benchmarks with respect to Lethality, Mobility, and Survivability
- Figure 3 is a three-dimensional plot of the candidates on axes representing the principal attributes
- Figures 4-6 are two-dimensional plots of the candidates on axes representing the principal attributes.

Place a weighting value after each entry using the following scale:
1: very helpful 2: helpful 3: neutral 4: not helpful

1.______________________________ ________

2.______________________________ ________

3.______________________________ ________

4.______________________________ ________

What did you like and/or dislike about the visual decision support tools, i.e. Figures 3 – 6?

____
____
____
____

Most tough decisions in the acquisition corps involve tradeoffs and concessions. This involves separating the 'nice-to-haves' from the 'must-haves'. From personal experience, what generic aspects of projects or programs do you feel are critical, and what are non-essential?

____
____
____
____

Appendix 6 (continued)

Please briefly define or list the qualities and metrics that come to mind when you consider these three principal attributes at the three levels of war.

Tactical Lethality____

Operational Lethality* ____

Strategic Lethality* ____

Tactical Mobility____

Operational Mobility ____

Strategic Mobility ____

Tactical Survivability____

Operational Survivability* ____

Strategic Survivability*____

*** term not addressed doctrinally for a tactical-level asset**

Appendix 7: Group 1 GCV Attribute Weighting Survey Raw Data

subject / criteria	IS01	IS02	IS03	IS04	IS05	IS06	IS07	IS09	IS10	IS12	IS14	IS15
L	0.41	0.25	0.59	0.32	0.16	0.11	0.15	0.26	0.14	0.20	0.16	0.14
M	0.26	0.16	0.16	0.12	0.30	0.44	0.22	0.19	0.33	0.49	0.54	0.53
S	0.33	0.59	0.25	0.56	0.54	0.44	0.63	0.55	0.53	0.31	0.30	0.33
TL	1	1	1	1	2	1	2	1	2	1	1	2
OL	2	1	2	2	3	3	1	2	2	2	2	4
SL	4	2	2	2	2	3	2	3	3	2	3	4
TM	1	1	1	1	1	1	2	1	2	1	1	1
OM	2	1	2	2	1	2	2	2	1	3	2	1
SM	2	2	1	2	3	1	2	3	2	1	4	2
TS	1	1	1	1	1	1	1	1	1	2	1	2
OS	1	1	1	2	1	2	1	2	2	3	3	2
SS	2	3	3	2	4	3	1	3	4	2	3	4
EB	0.33	0.11	0.54	0.12	0.40	0.14	0.13	0.63	0.16	0.62	0.16	0.12
IB	0.33	0.24	0.16	0.27	0.20	0.53	0.25	0.15	0.59	0.25	0.30	0.27
TB	0.33	0.65	0.30	0.61	0.40	0.33	0.62	0.22	0.25	0.13	0.54	0.61
BAD	9	9	7	10	4	8	8	10	2	10	9	9
CAL	7	6	6	4	6	4	7	8	5	6	1	5
F_recoil	8	10	10	6	9	9	1	5	10	9	7	7
KE	6	5	3	8	2	3	4	7	9	8	2	8
l_cannon	10	8	9	9	10	10	5	9	4	5	8	10
MER	2	1	2	2	3	2	6	2	6	1	3	2
P_kill	1	2	1	1	1	1	3	1	3	7	4	1
t_flight	4	3	5	3	8	7	9	3	8	3	10	4
t_reload	5	4	4	5	5	5	10	6	7	2	5	6
tuneable	3	7	8	7	7	6	2	4	1	4	6	3
cc	0.41	0.65	0.33	0.53	0.54	0.59	0.11	0.25	0.33	0.24	0.55	0.49
road	0.26	0.11	0.14	0.33	0.16	0.16	0.44	0.13	0.14	0.11	0.26	0.20
robust	0.33	0.24	0.53	0.14	0.30	0.25	0.44	0.62	0.53	0.65	0.19	0.31
cg	1	3	7	4	1	5	3	9	1	10	3	9
h_climb	2	9	3	5	3	2	10	8	5	5	4	8
P/w	5	4	1	6	7	4	4	7	8	7	7	10
range	4	1	5	8	4	7	8	1	9	1	1	2
r_turn	9	8	10	7	5	6	2	5	2	8	6	1
VCI_n	3	6	9	1	6	1	7	10	4	6	5	4
v_max	6	2	4	10	8	8	5	2	7	9	9	7
w_gap	8	10	8	2	9	3	1	6	6	3	10	5
etta_fuel	10	5	6	9	10	9	6	3	10	2	2	6
%_slope	7	7	2	3	2	10	9	4	3	4	6	3
repairable	0.33	0.24	0.20	0.12	0.16	0.24	0.11	0.11	0.16	0.10	0.25	0.14
susceptible	0.33	0.11	0.40	0.27	0.54	0.11	0.24	0.24	0.25	0.29	0.16	0.33
vulnerable	0.33	0.65	0.40	0.61	0.30	0.65	0.65	0.65	0.59	0.60	0.59	0.53
A_cross	3	4	2	4	1	6	5	5	9	6	5	2
A_foot	9	10	10	5	7	10	6	4	8	9	4	4
BPR	4	1	1	1	2	1	1	1	1	4	1	1
E_comb	5	3	9	6	3	9	4	6	7	3	6	7
e_m	2	5	3	2	4	7	9	3	6	5	10	9
h_clear	8	9	8	8	10	8	10	8	3	8	8	6
mass	7	8	7	9	8	5	3	7	5	7	7	10
modular	10	6	6	7	9	3	8	9	10	2	9	3
RHA_eq	1	2	4	3	5	2	7	2	2	1	2	8
v_hull	6	7	5	10	6	4	2	10	4	10	3	5

Appendix 7 (continued)

subject / criteria	IS01	IS02	IS03	IS04	IS05	IS06	IS07	IS09	IS10	IS12	IS14	IS15
A	0.46	0.48	0.48	0.49	0.45	0.42	0.47	0.48	0.44	0.41	0.40	0.40
B	0.45	0.42	0.47	0.43	0.41	0.41	0.40	0.42	0.41	0.42	0.42	0.42
C	0.23	0.23	0.23	0.23	0.22	0.21	0.22	0.23	0.22	0.21	0.21	0.21
D	0.33	0.36	0.29	0.34	0.37	0.38	0.37	0.35	0.38	0.36	0.37	0.37
E	0.18	0.18	0.16	0.17	0.19	0.20	0.19	0.18	0.19	0.20	0.20	0.20
F	0.31	0.28	0.34	0.30	0.27	0.26	0.27	0.29	0.26	0.27	0.26	0.26
from att: A	1	1	1	1	1	1	1	1	1	2	2	2
from at: B	2	2	2	2	2	2	2	2	2	1	1	1
from att: C	5	5	5	5	5	5	5	5	5	5	5	5
from att: D	3	3	4	3	3	3	3	3	3	3	3	3
from att: E	6	6	6	6	6	6	6	6	6	6	6	6
from att: F	4	4	3	4	4	4	4	4	4	4	4	4
choice: A	3	2	3	5	5	4	6	4	3	5	2	4
choice: B	5	3	5	6	2	2	4	2	6	2	5	5
choice: C	1	4	2	4	6	3	5	1	1	4	4	1
choice: D	4	5	1	2	3	1	1	5	4	3	1	3
choice: E	6	6	6	3	1	6	2	6	5	6	6	6
choice: F	2	1	4	1	4	5	3	3	2	1	3	2
diff L	0.13	0.04	0.31	0.03	0.12	0.17	0.13	0.02	0.15	0.09	0.12	0.15
diff M	0.01	0.11	0.11	0.15	0.03	0.18	0.05	0.08	0.06	0.23	0.27	0.26
diff S	0.12	0.15	0.20	0.11	0.09	0.00	0.18	0.10	0.08	0.14	0.15	0.11
sum	0.25	0.29	0.62	0.29	0.24	0.35	0.37	0.20	0.29	0.45	0.54	0.52
rank	3	8	23	7	2	12	13	1	5	18	21	19
IC A	2	1	2	4	4	3	5	3	2	3	0	2
IC B	3	1	3	4	0	0	2	0	4	1	4	4
IC C	4	1	3	1	1	2	0	4	4	1	1	4
IC D	1	2	3	1	0	2	2	2	1	0	2	0
IC E	0	0	0	3	5	0	4	0	1	0	0	0
IC F	2	3	1	3	0	1	1	1	2	3	1	2
sum	12	8	12	16	10	8	14	10	14	8	8	12
IC rank	14	2	14	22	7	2	18	7	18	2	2	14
EC1 A	2	1	2	4	4	3	5	3	2	4	1	3
EC1 B	3	1	3	4	0	0	2	0	4	0	3	3
EC1 C	4	1	3	1	1	2	0	4	4	1	1	4
EC1 D	1	2	2	1	0	2	2	2	1	0	2	0
EC1 E	0	0	0	3	5	0	4	0	1	0	0	0
EC1 F	2	3	0	3	0	1	1	1	2	3	1	2
sum	12	8	10	16	10	8	14	10	14	8	8	12
EC1 rank	14	2	7	22	7	2	19	7	19	2	2	14
EC2 A	0	0	0	0	0	0	0	0	0	1	1	1
EC2 B	0	0	0	0	0	0	0	0	0	1	1	1
EC2 C	0	0	0	0	0	0	0	0	0	0	0	0
EC2 D	0	0	1	0	0	0	0	0	0	0	0	0
EC2 E	0	0	0	0	0	0	0	0	0	0	0	0
EC2 F	0	0	1	0	0	0	0	0	0	0	0	0
sum	0	0	2	0	0	0	0	0	0	2	2	2
EC2 rank	1	1	17	1	1	1	1	1	1	17	17	17

Appendix 7 (continued)

subject / criteria	IS16	IS18	IS19	IS20	IS21	IS22	IS23	IS24	IS25	IS26	IS27	IS29
L	0.53	0.60	0.22	0.13	0.14	0.65	0.55	0.22	0.13	0.47	0.14	0.16
M	0.33	0.10	0.15	0.28	0.29	0.11	0.26	0.15	0.28	0.15	0.33	0.25
S	0.14	0.29	0.63	0.58	0.57	0.24	0.19	0.63	0.58	0.38	0.53	0.59
TL	1	1	1	1	2	1	1	1	1	1	2	2
OL	2	2	1	2	2	2	2	2	2	1	3	3
SL	3	3	1	3	1	3	2	1	3	2	3	4
TM	4	1	1	1	1	1	1	3	1	1	1	1
OM	4	1	1	2	1	2	2	3	2	2	1	2
SM	4	1	1	3	2	3	2	1	3	1	1	1
TS	1	1	1	1	1	1	1	1	1	1	2	1
OS	2	2	1	2	1	2	2	1	2	2	1	3
SS	3	3	1	3	3	3	3	4	3	2	3	4
EB	0.11	0.50	0.15	0.13	0.13	0.13	0.14	0.28	0.33	0.20	0.20	0.16
IB	0.24	0.25	0.22	0.28	0.21	0.28	0.24	0.28	0.33	0.28	0.40	0.30
TB	0.65	0.25	0.63	0.58	0.66	0.58	0.62	0.44	0.33	0.52	0.40	0.54
BAD	9	6	3	10	4	8	8	10	3	7	7	10
CAL	5	4	7	3	5	7	7	9	2	6	6	5
F_recoil	7	10	2	9	10	9	9	7	10	9	8	4
KE	8	5	9	2	3	3	6	5	8	8	10	6
l_cannon	10	9	1	5	9	10	10	6	6	10	9	9
MER	1	3	8	1	2	2	5	8	5	2	4	2
P_kill	2	1	10	4	1	1	1	1	1	1	2	1
t_flight	4	8	6	7	8	5	4	3	9	4	5	7
t_reload	6	2	5	6	7	6	3	4	4	3	3	3
tuneable	3	7	4	8	6	4	2	2	7	5	1	8
cc	0.32	0.33	0.22	0.58	0.53	0.28	0.64	0.22	0.49	0.54	0.48	0.62
roadworthy	0.12	0.33	0.15	0.28	0.14	0.58	0.18	0.15	0.20	0.16	0.35	0.14
robust	0.56	0.33	0.63	0.13	0.33	0.13	0.18	0.63	0.31	0.30	0.17	0.24
cg	9	4	4	2	10	6	5	5	2	10	2	2
h_climb	4	6	3	3	7	5	9	6	10	9	5	1
P/w	10	7	9	10	1	4	1	4	8	8	4	5
range	1	3	5	9	3	1	3	3	4	1	8	7
r_turn	7	2	6	8	6	8	2	9	5	7	7	8
VCI_n	6	8	2	6	5	9	4	10	3	3	6	4
v_max	2	1	10	5	4	2	8	2	6	2	9	10
w_gap	8	5	1	1	9	6	7	8	9	4	10	6
etta_fuel	5	10	7	4	8	7	10	1	1	5	3	9
%_slope	3	9	8	7	2	10	6	7	7	6	1	3
repairable	0.14	0.17	0.15	0.13	0.13	0.13	0.18	0.18	0.30	0.30	0.31	0.27
susceptible	0.43	0.39	0.22	0.28	0.21	0.25	0.18	0.23	0.16	0.16	0.20	0.12
vulnerable	0.43	0.44	0.63	0.58	0.66	0.62	0.64	0.58	0.54	0.54	0.49	0.61
A_cross	4	3	8	3	5	3	5	7	6	5	10	10
A_foot	8	4	7	7	6	6	6	6	7	6	2	9
BPR	1	1	10	1	1	1	1	5	1	1	1	1
E_comb	3	5	4	6	7	5	10	4	2	7	4	3
e_m	5	8	1	5	9	4	4	8	8	9	7	7
h_clear	10	6	2	4	4	7	3	9	3	10	8	4
mass	9	9	3	3	3	8	8	1	5	3	3	8
modular	6	10	6	9	8	9	9	2	9	8	9	5
RHA_eq	2	2	9	2	10	2	5	3	4	2	5	6
v_hull	7	7	5	10	2	10	2	10	10	4	6	2

Appendix 7 (continued)

subject / criteria	IS16	IS18	IS19	IS20	IS21	IS22	IS23	IS24	IS25	IS26	IS27	IS29
A	0.44	0.49	0.49	0.46	0.46	0.49	0.45	0.49	0.46	0.48	0.44	0.46
B	0.47	0.47	0.41	0.40	0.40	0.48	0.47	0.41	0.40	0.45	0.41	0.40
C	0.22	0.24	0.23	0.22	0.22	0.24	0.23	0.23	0.22	0.23	0.22	0.22
D	0.30	0.29	0.36	0.38	0.38	0.28	0.30	0.36	0.38	0.31	0.38	0.37
E	0.17	0.16	0.18	0.19	0.19	0.16	0.17	0.18	0.19	0.17	0.19	0.19
F	0.32	0.34	0.28	0.26	0.26	0.35	0.33	0.28	0.26	0.32	0.26	0.27
from att…A	2	1	1	1	1	1	2	1	1	1	1	1
from att…B	1	2	2	2	2	2	1	2	2	2	2	2
from att…C	5	5	5	5	5	5	5	5	5	5	5	5
from att…D	4	4	3	3	3	4	4	3	3	4	3	3
from att…E	6	6	6	6	6	6	6	6	6	6	6	6
from att…F	3	3	4	4	4	3	3	4	4	3	4	4
choice...A	3	3	4	4	6	5	4	3	6	1	2	4
choice...B	5	6	1	5	5	6	2	4	5	2	5	5
choice...C	1	5	6	6	4	3	2	6	4	3	3	3
choice...D	4	1	2	1	1	2	3	1	2	4	4	2
choice...E	6	2	3	2	3	4	6	5	3	5	6	6
choice...F	2	4	5	3	2	1	1	2	1	6	1	1
wting diff L	0.24	0.32	0.07	0.15	0.14	0.37	0.26	0.07	0.15	0.19	0.15	0.13
wting diff M	0.06	0.16	0.12	0.01	0.02	0.16	0.00	0.12	0.01	0.12	0.06	0.02
wting diff S	0.31	0.16	0.18	0.14	0.13	0.21	0.26	0.18	0.14	0.07	0.08	0.15
sum	0.61	0.64	0.37	0.30	0.29	0.73	0.52	0.37	0.30	0.38	0.29	0.29
rank	22	24	13	10	4	25	20	13	10	16	5	8
IC A	1	2	3	3	5	4	2	2	5	0	1	3
IC B	4	4	1	3	3	4	1	2	3	0	3	3
IC C	4	0	1	1	1	2	3	1	1	2	2	2
IC D	0	3	1	2	2	2	1	2	1	0	1	1
IC E	0	4	3	4	3	2	0	1	3	1	0	0
IC F	1	1	1	1	2	2	2	2	3	3	3	3
sum	10	14	10	14	16	16	9	10	16	6	10	12
IC rank	7	18	7	18	22	22	6	7	22	1	7	14
EC1 A	2	2	3	3	5	4	3	2	5	0	1	3
EC1 B	3	4	1	3	3	4	0	2	3	0	3	3
EC1 C	4	0	1	1	1	2	3	1	1	2	2	2
EC1 D	1	2	1	2	2	1	0	2	1	1	1	1
EC1 E	0	4	3	4	3	2	0	1	3	1	0	0
EC1 F	2	0	1	1	2	3	3	2	3	2	3	3
sum	12	12	10	14	16	16	9	10	16	6	10	12
EC1 rank	14	14	7	19	22	22	6	7	22	1	7	14
EC2 A	1	0	0	0	0	0	1	0	0	0	0	0
EC2 B	1	0	0	0	0	0	1	0	0	0	0	0
EC2 C	0	0	0	0	0	0	0	0	0	0	0	0
EC2 D	1	1	0	0	0	1	1	0	0	1	0	0
EC2 E	0	0	0	0	0	0	0	0	0	0	0	0
EC2 F	1	1	0	0	0	1	1	0	0	1	0	0
sum	4	2	0	0	0	2	4	0	0	2	0	0
EC2 rank	24	17	1	1	1	17	24	1	1	17	1	1

Appendix 8: Group 2 GCV Attribute Weighting Survey Raw Data

criteria \ subject	IN01	IN02	IN03	IN04	IN05	IN06	IN07	IN08	IN09	IN10	IN11	IN12
L	0.32	0.46	0.25	0.28	0.30	0.28	0.33	0.36	0.26	0.25	0.33	0.30
M	0.22	0.22	0.13	0.13	0.16	0.13	0.33	0.12	0.10	0.13	0.26	0.12
S	0.46	0.32	0.62	0.58	0.54	0.58	0.33	0.52	0.64	0.62	0.41	0.57
TL	2	1	3	2	2	1	2	1	2	3	1	2
OL	5	2	2	5	4	3	3	3	4	2	3	5
SL	1	3	1	1	1	2	1	5	1	1	2	1
TM	4	4	6	4	5	4	7	4	3	8	4	4
OM	6	5	5	6	6	6	4	6	5	4	6	6
SM	3	6	4	3	3	5	6	5	2	6	5	3
TS	8	8	9	8	8	7	9	7	4	9	7	8
OS	9	7	8	9	9	9	5	9	5	5	9	9
SS	7	9	7	7	7	8	8	8	2	7	8	7
EB	0.16	0.17	0.12	0.16	0.24	0.32	0.33	0.20	0.11	0.20	0.22	0.11
IB	0.25	0.17	0.27	0.25	0.21	0.22	0.33	0.40	0.24	0.31	0.37	0.24
TB	0.59	0.67	0.61	0.59	0.55	0.46	0.33	0.40	0.65	0.49	0.41	0.65
BAD	10	10	7	9	10	5	10	6	10	9	10	10
CAL	3	5	8	3	7	8	3	5	2	5	3	3
F_recoil	8	6	9	7	1	7	8	7	7	6	5	8
KE	5	4	1	2	9	4	7	2	9	1	4	5
l_cannon	9	7	10	8	8	9	9	10	8	8	7	9
MER	2	3	2	4	4	1	2	1	5	2	8	2
P_kill	1	1	5	1	2	2	1	3	1	7	1	1
t_flight	7	9	6	10	5	6	6	8	6	3	9	7
t_reload	6	2	3	5	3	3	5	4	3	4	6	6
tuneable	4	8	4	6	6	10	4	9	4	10	2	4
cc	0.43	0.32	0.61	0.62	0.46	0.42	0.46	0.41	0.58	0.33	0.49	0.63
road	0.14	0.22	0.12	0.13	0.29	0.13	0.22	0.22	0.13	0.26	0.20	0.19
robust	0.43	0.46	0.27	0.25	0.25	0.46	0.32	0.37	0.28	0.41	0.31	0.17
cg	3	6	4	1	10	7	7	1	1	1	3	3
h_climb	9	7	3	6	6	1	8	10	3	8	10	9
P/w	4	8	5	2	1	8	9	4	2	9	7	4
range	1	5	2	4	9	5	3	2	8	2	1	1
r_turn	7	4	9	7	4	2	10	7	7	5	2	7
VCI_n	10	10	10	8	8	9	4	8	10	4	5	10
v_max	2	3	1	5	3	6	1	3	4	10	4	2
w_gap	8	9	8	10	5	3	2	9	6	6	6	8
etta_fuel	5	1	6	3	7	10	5	5	9	7	8	5
%_slope	6	2	7	9	2	4	6	6	5	3	9	6
repairable	0.16	0.33	0.13	0.16	0.20	0.20	0.22	0.26	0.11	0.33	0.24	0.12
susceptible	0.25	0.33	0.25	0.30	0.20	0.20	0.46	0.33	0.24	0.33	0.21	0.27
vulnerable	0.59	0.33	0.62	0.54	0.60	0.60	0.32	0.41	0.65	0.33	0.55	0.61
A_cross	4	10	9	1	3	4	2	1	8	5	7	4
A_foot	7	7	1	8	4	9	7	4	9	8	8	7
BPR	3	3	8	4	1	3	1	3	1	2	1	3
E_comb	6	6	10	7	5	8	8	9	5	3	4	6
e_m	2	8	7	3	2	2	5	8	7	6	6	2
h_clear	8	4	2	9	7	7	9	7	6	9	10	8
mass	9	5	3	5	6	6	10	6	3	10	5	9
modular	10	9	4	10	9	10	6	2	10	7	9	10
RHA_eq	1	2	6	2	8	1	3	5	2	4	2	1
v_hull	5	1	5	6	10	5	4	10	4	1	3	5

Appendix 8 (continued)

subject criteria	IN01	IN02	IN03	IN04	IN05	IN06	IN07	IN08	IN09	IN10	IN11	IN12
A	0.58	0.66	0.53	0.55	0.56	0.55	0.60	0.59	0.53	0.53	0.59	0.56
B	0.42	0.43	0.41	0.41	0.41	0.41	0.44	0.41	0.40	0.41	0.43	0.41
C	0.77	0.72	0.84	0.83	0.81	0.83	0.71	0.80	0.85	0.84	0.75	0.82
D	0.54	0.59	0.47	0.48	0.50	0.48	0.60	0.51	0.46	0.47	0.56	0.48
E	0.42	0.45	0.35	0.36	0.38	0.36	0.50	0.36	0.33	0.35	0.45	0.35
F	0.66	0.58	0.71	0.69	0.68	0.69	0.64	0.65	0.71	0.71	0.65	0.68
from att: A	3	2	3	3	3	3	3	3	3	3	3	3
from at: B	5	6	5	5	5	5	6	5	5	5	6	5
from att: C	1	1	1	1	1	1	1	1	1	1	1	1
from att: D	4	3	4	4	4	4	4	4	4	4	4	4
from att: E	6	5	6	6	6	6	5	6	6	6	5	6
from att: F	2	4	2	2	2	2	2	2	2	2	2	2
choice: A	2	5	3	4	6	2	3	4	5	2	3	2
choice: B	3	6	2	2	5	5	5	3	4	6	6	5
choice: C	1	4	1	2	4	1	1	5	1	3	1	1
choice: D	4	3	4	1	1	4	2	6	6	1	4	3
choice: E	6	1	5	6	3	6	6	2	3	5	5	6
choice: F	5	2	6	3	2	3	4	1	2	4	2	4
diff L	0.02	0.16	0.05	0.02	0.00	0.02	0.03	0.06	0.04	0.05	0.03	0.01
diff M	0.04	0.04	0.05	0.05	0.02	0.05	0.15	0.06	0.08	0.05	0.07	0.06
diff S	0.06	0.20	0.11	0.07	0.02	0.07	0.18	0.00	0.13	0.11	0.10	0.06
sum	0.11	0.39	0.21	0.14	0.05	0.14	0.36	0.12	0.26	0.21	0.21	0.13
rank	4	21	13	7	1	7	18	5	16	13	11	6
IC A	1	3	0	1	3	1	0	1	2	1	0	1
IC B	2	0	3	3	0	0	1	2	1	1	0	0
IC C	0	3	0	1	3	0	0	4	0	2	0	0
IC D	0	0	0	3	3	0	2	2	2	3	0	1
IC E	0	4	1	0	3	0	1	4	3	1	0	0
IC F	3	2	4	1	0	1	2	1	0	2	0	2
sum	6	12	8	9	12	2	6	14	8	10	0	4
IC rank	8	18	12	16	18	4	8	20	12	17	1	6
EC1 A	1	2	0	1	3	1	0	1	2	1	0	1
EC1 B	2	1	3	3	0	0	0	2	1	1	1	0
EC1 C	0	3	0	1	3	0	0	4	0	2	0	0
EC1 D	0	1	0	3	3	0	2	2	2	3	0	1
EC1 E	0	5	1	0	3	0	0	4	3	1	1	0
EC1 F	3	0	4	1	0	1	2	1	0	2	0	2
sum	6	12	8	9	12	2	4	14	8	10	2	4
EC1 rank	10	18	12	15	18	3	6	20	12	16	3	6
EC2 A	0	1	0	0	0	0	0	0	0	0	0	0
EC2 B	0	1	0	0	0	0	1	0	0	0	1	0
EC2 C	0	0	0	0	0	0	0	0	0	0	0	0
EC2 D	0	1	0	0	0	0	0	0	0	0	0	0
EC2 E	0	1	0	0	0	0	1	0	0	0	1	0
EC2 F	0	2	0	0	0	0	0	0	0	0	0	0
sum	0	6	0	0	0	0	2	0	0	0	2	0
EC2 rank	1	21	1	1	1	1	16	1	1	1	16	1

Appendix 8 (continued)

subject criteria	IN12	IN13	IN14	IN15	IN16	IN17	IN18	IN19	IN20	IN21
L	0.30	0.24	0.28	0.17	0.33	0.25	0.33	0.33	0.33	0.30
M	0.12	0.13	0.13	0.17	0.33	0.16	0.14	0.26	0.33	0.16
S	0.57	0.62	0.58	0.67	0.33	0.59	0.53	0.41	0.33	0.54
TL	2	7	1	2	1	4	2	5	4	3
OL	4	6	2	3	3	2	3	7	1	1
SL	7	1	3	1	2	1	1	2	9	2
TM	3	5	4	5	6	6	5	3	5	6
OM	5	9	5	6	4	8	6	1	2	4
SM	6	2	6	4	5	5	4	4	8	5
TS	1	4	7	9	8	7	8	8	6	9
OS	8	8	8	7	9	9	9	9	3	7
SS	9	3	9	8	7	3	7	6	7	8
EB	0.11	0.13	0.12	0.26	0.33	0.25	0.16	0.14	0.17	0.33
IB	0.24	0.25	0.27	0.33	0.33	0.25	0.30	0.33	0.17	0.33
TB	0.65	0.62	0.61	0.41	0.33	0.50	0.54	0.53	0.67	0.33
BAD	10	8	10	3	10	8	10	2	8	10
CAL	3	7	6	4	2	5	3	4	9	2
F_recoil	9	9	9	8	3	9	9	8	7	7
KE	7	3	7	9	1	7	6	7	4	5
l_cannon	8	10	8	10	7	10	8	10	10	8
MER	5	2	2	2	5	1	2	9	2	3
P_kill	1	1	1	1	6	2	1	1	1	1
t_flight	6	5	5	6	8	6	7	6	5	6
t_reload	2	4	3	7	4	3	4	3	6	4
tuneable	4	6	4	5	9	4	5	5	3	9
cc	0.63	0.57	0.54	0.41	0.44	0.49	0.46	0.58	0.67	0.33
roadworthy	0.19	0.12	0.16	0.26	0.17	0.20	0.32	0.18	0.17	0.26
robust	0.17	0.30	0.30	0.33	0.39	0.31	0.22	0.23	0.17	0.41
cg	1	5	2	10	5	4	7	2	3	5
h_climb	4	10	8	2	4	3	5	6	7	6
P/w	2	2	1	1	1	10	8	9	1	7
range	5	1	3	6	6	9	1	1	2	1
r_turn	3	6	7	3	7	8	6	3	8	10
VCI_n	8	9	4	9	3	1	9	5	4	8
v_max	6	3	6	7	8	5	2	7	5	2
w_gap	9	7	9	5	10	7	10	10	10	9
etta_fuel	10	4	10	4	2	6	4	4	6	3
%_slope	7	8	5	8	9	2	3	8	9	4
repairable	0.12	0.13	0.12	0.15	0.32	0.16	0.23	0.12	0.33	0.19
susceptible	0.27	0.25	0.27	0.38	0.22	0.25	0.18	0.27	0.33	0.26
vulnerable	0.61	0.62	0.61	0.47	0.46	0.59	0.58	0.61	0.33	0.55
A_cross	5	4	5	4	9	2	7	9	4	4
A_foot	10	5	6	7	10	8	5	4	3	5
BPR	3	1	1	3	1	1	6	1	8	1
E_comb	4	6	9	5	3	9	10	7	6	6
e_m	7	8	10	6	6	6	9	6	10	8
h_clear	8	9	8	8	8	4	4	5	2	7
mass	9	10	3	10	7	10	2	10	1	2
modular	6	7	7	9	2	7	8	3	5	10
RHA_eq	2	2	2	2	5	5	1	8	9	9
v_hull	1	3	4	1	4	3	3	2	7	3

Appendix 8 (continued)

subject / criteria	IN12	IN13	IN14	IN15	IN16	IN17	IN18	IN19	IN20	IN21
A	0.56	0.53	0.55	0.49	0.60	0.53	0.58	0.59	0.60	0.56
B	0.41	0.41	0.41	0.41	0.44	0.41	0.41	0.43	0.44	0.41
C	0.82	0.84	0.83	0.85	0.71	0.83	0.81	0.75	0.71	0.81
D	0.48	0.47	0.48	0.46	0.60	0.48	0.50	0.56	0.60	0.50
E	0.35	0.35	0.36	0.36	0.50	0.36	0.37	0.45	0.50	0.38
F	0.68	0.71	0.69	0.74	0.64	0.70	0.66	0.65	0.64	0.68
from att A	3	3	3	3	3	3	3	3	3	3
from att B	5	5	5	5	6	5	5	6	6	5
from att C	1	1	1	1	1	1	1	1	1	1
from att D	4	4	4	4	4	4	4	4	4	4
from att E	6	6	6	6	5	6	6	5	5	6
from att F	2	2	2	2	2	2	2	2	2	2
choice...A	2	5	4	3	4	3	4	6	4	3
choice...B	5	4	5	5	3	5	3	5	6	2
choice...C	1	3	1	1	1	1	1	2	2	1
choice...D	3	2	3	4	5	4	5	3	5	4
choice...E	6	6	6	6	6	6	6	4	1	6
choice...F	4	1	2	2	2	2	2	1	3	5
wting diff L	0.01	0.05	0.02	0.13	0.03	0.05	0.03	0.03	0.03	0.00
wting diff M	0.06	0.05	0.05	0.02	0.15	0.03	0.05	0.07	0.15	0.02
wting diff S	0.06	0.11	0.07	0.15	0.18	0.08	0.01	0.10	0.18	0.02
sum	0.13	0.22	0.14	0.30	0.36	0.16	0.09	0.21	0.36	0.05
rank	6	15	7	17	18	10	3	11	18	1
IC A	1	2	1	0	1	0	1	3	1	0
IC B	0	1	0	0	3	0	2	1	0	3
IC C	0	2	0	0	0	0	0	1	1	0
IC D	1	2	1	0	1	0	1	1	1	0
IC E	0	0	0	0	1	0	0	1	4	0
IC F	2	1	0	0	0	0	0	1	1	3
sum	4	8	2	0	6	0	4	8	8	6
IC rank	6	12	4	1	8	1	6	12	12	8
EC1 A	1	2	1	0	1	0	1	3	1	0
EC1 B	0	1	0	0	2	0	2	0	1	3
EC1 C	0	2	0	0	0	0	0	1	1	0
EC1 D	1	2	1	0	1	0	1	1	1	0
EC1 E	0	0	0	0	0	0	0	2	5	0
EC1 F	2	1	0	0	0	0	0	1	1	3
sum	4	8	2	0	4	0	4	8	10	6
EC1 rank	6	12	3	1	6	1	6	12	17	10
EC2 A	0	0	0	0	0	0	0	0	0	0
EC2 B	0	0	0	0	1	0	0	1	1	0
EC2 C	0	0	0	0	0	0	0	0	0	0
EC2 D	0	0	0	0	0	0	0	0	0	0
EC2 E	0	0	0	0	1	0	0	1	1	0
EC2 F	0	0	0	0	0	0	0	0	0	0
sum	0	0	0	0	2	0	0	2	2	0
EC2 rank	1	1	1	1	16	1	1	16	16	1

Appendix 9: Ground Combat Vehicle Mission Simulation Survey

Modified Title: ***Ground Combat Vehicle Mission Simulation Survey***
IRB PROTOCOL # 2010090027
Conducted By: Joshua M. Keena
Of The University of Texas at Austin: *Department / Office*; ME/4.11126 Telephone: 232-4471

You are being asked to participate in a research study. This form provides you with information about the study. The person in charge of this research will also describe this study to you and answer all of your questions. Please read the information below and ask any questions you might have before deciding whether or not to take part. Your participation is entirely voluntary. You can refuse to participate or stop participating at any time without penalty or loss of benefits to which you are otherwise entitled. You can stop your participation at any time and your refusal will not impact current or future relationships with UT Austin or participating sites. To do so simply tell the researcher you wish to stop participation. The researcher will provide you with a copy of this consent for your records.

The purpose of this study is to capture the performance of prototypic ground combat vehicles in a simulated environment. I intend to interview up to 20 ROTC cadets for this study.

If you agree to be in this study, we will ask you to do the following things:

- Participants will be oriented to the software title through a short presentation
- Participants will conduct a series of user familiarization and training exercises using the aforementioned software
- Participants will be asked to use a series of vehicle variants in a similar mission environment and record the performance of each vehicle at the completion of the exercise

Total estimated time to participate in study is 4 hours (including 1 hour for lunch)

Risks of being in the study are no greater than everyday life.

Benefits of being in the study include exposure to the design process and requisite considerations for trade off analysis with respect to ground combat vehicles.

Compensation: A lunch meal will be served from a local caterer.

Confidentiality and Privacy Protections:
The data resulting from your participation may be made available to other researchers in the future for research purposes not detailed within this consent form. In these cases, the data will contain no identifying information that could associate you with it, or with your participation in any study.

The records of this study will be stored securely and kept confidential. Authorized persons from The University of Texas at Austin, members of the Institutional Review Board, and (study sponsors, if any) have the legal right to review your research records and will protect the confidentiality of those records to the extent permitted by law. All publications will exclude any information that will make it possible to identify you as a subject. Throughout the study, the researchers will notify you of new information that may become available and that might affect your decision to remain in the study.

Contacts and Questions:

If you have any questions about the study please ask now. If you have questions later, want additional information, or wish to withdraw your participation call the researchers conducting the study. Their names, phone numbers, and e-mail addresses are at the top of this page.

If you would like to obtain information about the research study, have questions, concerns, complaints or wish to discuss problems about a research study with someone unaffiliated with the study, please contact the IRB Office at (512) 471-8871 or Jody Jensen, Ph.D., Chair, The University of Texas at Austin Institutional Review Board for the Protection of Human Subjects at (512) 232-2685. Anonymity, if desired, will be protected to the extent possible. As an alternative method of contact, an email may be sent to orsc@uts.cc.utexas.edu or a letter sent to IRB Administrator, P.O. Box 7426, Mail Code A 3200, Austin, TX 78713.

You will be given a copy of this information to keep for your records.

Appendix 9 (continued)

Statement of Consent:

I have read the above information and have sufficient information to make a decision about participating in this study. I consent to participate in the study.

Signature:____ Date: ___________________

____ Date: ____________________
Signature of Person Obtaining Consent / Investigator

Appendix 10: IRB Study Amendment for Combat Vehicle Simulations

IRB Amendment to Study 2010090027
Attribute Weighting Survey Questionnaire for Ground Combat Vehicle Design and Selection Considerations

Joshua M. Keena
PhD Candidate, Mechanical Engineering
University of Texas at Austin

VII. **Modified Title: Ground Combat Vehicle Mission Simulation Survey**

VIII. **Investigators (co-investigators): Joshua M. Keena** *no change*

IX. **Hypothesis, Research Questions, or Goals of the Project:** The goal of this project is to capture the quantitative results of prototypic ground combat vehicle design performance in a simulated game environment as controlled by soldiers and ROTC cadets.

X. **Background and Significance**: *no change*

The design and/or selection of a ground combat vehicle is often an exercise in trade-offs enabled by appropriate decision support tools. In order to aid in the compilation and distillation of performance data, measurable attributes are often weighted appropriately (Saaty, 1977). By querying a statistical sample of the user population with questions focused on capturing the subjective weightings each places on the various performance aspects of a ground combat vehicle candidate, these weightings can subsequently be used either to guide design efforts and resources or to streamline selection processes.

XI. **Research Method, Design, and Proposed Statistical Analysis:**

I will present the participants with a short presentation about the software title to be used in the exercise. This is essentially a game where the user navigates a ground combat vehicle through an urban environment in order to conduct a notional mission to seek and destroy a peer threat vehicle. After conducting an orientation to the software and hardware, e.g. joystick, the participants will conduct a familiarization mission to gain basic experience and proficiency with the game. Upon completion of the training mission, the users will be asked to deploy vehicle variants through the same mission scenario. Users will be asked to record performance data for each vehicle. This information appears on the closing screen after a simulation, and this screenshot includes data regarding mission success, time for mission, and vehicle health rating for friend and foe. Since the variants have been designed using a DOE methodology, the variant performance can be subsequently analyzed to elicit attribute weighting significance and possible interactions between these attributes.

Appendix 10 (continued)

XII. Human Subject Interactions

A. The potential participants will be members of the University of Texas ROTC Program that includes transitioning service members as well as newly assessed cadets. The population will be both male and female cadets, aged approximately from 20-40. The total population of participants will number approximately 20 subjects. In accordance with military regulations and standards, all participants will be in good health. Given the fact that the population will be composed of cadets in training to become leaders and military officers, it is unlikely that any of the participants are apt to be vulnerable to coercion or undue influence. All students enrolled in the ROTC Program meet screening criteria and are eligible for inclusion in the study. Participation will of course be voluntary, and there will be an alternate activity available for those not wishing to contribute to this research project. I expect human subject involvement in this project to begin in January 2011 and to end in February 2011.

B. I am currently in discourse with the Professor of Military Science for the ROTC Program at the University of Texas regarding this survey. If he agrees to make his cadets available for this study, and if this amendment is approved, then we will use a period of discretionary time to conduct this exercise. As members of the ROTC program, all subjects have been prescreened and are fully qualified, both professionally and academically, to participate in this study.

C. I will present all participants with a consent form and maintain copies with my confidential research archives. Additionally, each participant will be given a copy of the signed consent form.

D. Research Protocol. I will present the participants with a short presentation about the software title to be used in the exercise. This is essentially a game where the user navigates a ground combat vehicle through an urban environment in order to conduct a notional mission to seek and destroy a peer threat vehicle. After conducting an orientation to the software and hardware, e.g. joystick, the participants will conduct a familiarization mission to gain basic experience and proficiency with the game. Upon completion of the training mission, the users will be asked to deploy vehicle variants through the same mission scenario. Users will be asked to record performance data for each vehicle. This information appears on the closing screen after a simulation, and this screenshot includes data regarding mission success, time for mission, and vehicle health rating for friend and foe.

E. I will protect and observe the privacy of each participant by only contacting them with follow up questions using methods they have agreed to on the questionnaire. Furthermore, I will contact them during times that they have indicated are acceptable (e.g., a professional email account ‘army knowledge online’ or ‘ako’).

F. I will protect the confidentiality of participants by maintaining strict control of all questionnaires in a locked file cabinet maintained in my office at the IAT, room 4.11126. I will not divulge to others any data that is inconsistent with the understanding of the original disclosure. The names will only be recorded on the original survey. All digital entries and subsequent analysis will rely on a code generated for confidentiality purposes. I will destroy this data within 12 months, no later than August 31, 2011.

H. The IQC coordinator has afforded me access to the course population during a period of discretionary time. We will conduct the survey in an established conference room.

VII. I rate this survey exercise as low risk. If, for unforeseen circumstances, I lose confidentiality of the participants' responses, I will notify the participants of this through established contact methods.

VIII. The participants could benefit from contributing to this project because they will be exposed to an organizational framework for cataloging and weighting the various principal and derivative metrics used to quantify the relative merit of a ground combat system. Since the participants are training to become leaders in the military, this subject is apropos for the range of specialists I anticipate engaging with. The benefits of participation heavily outweigh the risks.

IX. No other sites or agencies are involved in this research project.

XI. This project will not receive review from another IRB.

Respectfully,
Joshua M. Keena
PhD candidate

Appendix 11: GCV Simulation Survey

Part I: Introduction

In support of the construction of a decision support tool being used in both the design and selection of the next Ground Combat Vehicle (GCV) candidate, you have been asked to deploy a prototypic vehicle in a simulated environment to collect performance data for this effort. At this early stage, consider the GCV as the successor to the Bradley Infantry Fighting Vehicle (M2A3 IFV). Your contribution to this study should be a reflection of your past military experiences, present duty position, and, perhaps toughest of all to predict, what you foresee to be the needs and capabilities of our future armed forces. Undoubtedly, the potential combat scenarios for future warfighters include a mix of both conventional (e.g. Desert Storm) and irregular warfare (e.g. OIF, OEF).

In the context of this exercise, you are going to focus strictly on combat platform performance. Cost and schedule considerations are being addressed in a subsequent forum. Moreover, with respect to performance, consider the worth of a ground combat vehicle to be a function of its principal attributes of Lethality, Survivability and Mobility. These three principal attributes can be further broken down into secondary traits and tertiary metrics.

While the GCV is clearly a platform that will operate as a tactical level asset, one should also consider the operational and strategic implications of the principal metrics. Some of these are easy to conceptualize (e.g. Strategic Mobility, like intertheater transportability), and others are more abstract notions (e.g. Operational Lethality, like collateral damage incurred). For tactical assets, it is normally easier to envision the negative operational and strategic implications of the principal attributes. In any case, use your best judgment when providing your rankings and feedback.

Part II: Background Information

ROTC Branch____

Prior Service (MOS, Service) __________________________________

Combat Experience (if applicable) _____________________________

Gaming Experience (on a scale of 1-5 with a 1 being inexperienced and a 5 is an expert)___________

Gaming Participation (hours per week) __________________________

Appendix 12: Script for Ground Combat Vehicle Simulation Exercise

Amended Script for Ground Combat Vehicle Simulation Survey

In support of the construction of a decision support tool being used in both the design and selection of the next Ground Combat Vehicle (GCV) candidate, you have been asked to deploy a prototypic vehicle in a simulated environment to collect performance data for this effort. At this early stage, consider the GCV as the successor to the Bradley Infantry Fighting Vehicle (M2A3 IFV). Your contribution to this study should be a reflection of your past military experiences, present duty position, and, perhaps toughest of all to predict, what you foresee to be the needs and capabilities of our future armed forces. Undoubtedly, the potential combat scenarios for future warfighters include a mix of both conventional (e.g. Desert Storm) and irregular warfare (e.g. OIF, OEF).

In the context of this exercise, you are going to focus strictly on combat platform performance. Cost and schedule considerations are being addressed in a subsequent forum. Moreover, with respect to performance, consider the worth of a ground combat vehicle to be a function of its principal attributes of Lethality, Survivability and Mobility. These three principal attributes can be further broken down into secondary traits and tertiary metrics.

While the GCV is clearly a platform that will operate as a tactical level asset, one should also consider the operational and strategic implications of the principal metrics. Some of these are easy to conceptualize (e.g. Strategic Mobility, like intertheater transportability), and others are more abstract notions (e.g. Operational Lethality, like collateral damage incurred). For tactical assets, it is normally easier to envision the negative operational and strategic implications of the principal attributes. In any case, use your best judgment when providing your rankings and feedback.

Appendix 13: Workstation Assignment Matrix

Tracked Vehicle Matrix (XTVs 1-8)

workstation	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
0-20 min	3	5	2	8	4	5	6	1	2	6	1	4	8	5	3	7
20–40 min	5	6	8	1	3	2	4	7	6	1	5	7	4	2	8	3
40-60 min	6	2	5	3	7	8	1	4	4	8	3	6	2	7	5	1
60-80 min	8	1	3	5	6	4	7	2	8	3	7	1	6	4	2	5

Wheeled Vehicle Matrix (XWVs 1-8)

workstation	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
0-20 min	8	1	5	7	4	2	6	3	5	2	3	1	4	7	6	8
20–40 min	6	4	2	5	3	8	1	7	3	1	8	7	2	4	5	6
40-60 min	4	5	1	3	7	6	2	8	1	6	7	5	8	3	2	4
60-80 min	1	7	6	8	5	3	4	2	6	3	4	2	5	8	7	1

Appendix 14: Combat Simulation Scoring Sheet

Vehicle _____________ Work Station_____________

Win / Loss [W or L]	Time [min:sec]	V1 health [%]	V2 health [%]

Vehicle _____________ Work Station_____________

Win / Loss [W or L]	Time [min:sec]	V1 health [%]	V2 health [%]

Appendix 15: XTV Raw Data

Data ► **Variant ▼**	**win %**	**blue %**	**red %**	**time %**	**timeout %**	**1-5 win %**
XTV1 − − − s l m	40%	85%	38%	73%	20%	29%
XTV2 + − − S l m	27%	81%	52%	76%	28%	20%
XTV3 − + − s L m	74%	88%	22%	54%	7%	73%
XTV4 + + − S L m	68%	92%	27%	55%	6%	63%
XTV5 − − + s l M	76%	84%	16%	64%	10%	70%
XTV6 + − + S l M	52%	80%	38%	62%	6%	50%
XTV7 − + + s L M	77%	93%	19%	45%	2%	73%
XTV8 + + + S L M	80%	91%	16%	42%	3%	77%

Appendix 16: XWV Raw Data

Data ► **Variant ▼**	**win %**	**blue %**	**red %**	**time %**	**timeout %**	**1-5 win %**
XWV1 − − − s l m	68%	84%	19%	42%	1%	66%
XWV2 + − − S l m	49%	84%	31%	57%	5%	44%
XWV3 − + − s L m	79%	92%	13%	26%	0%	74%
XWV4 + + − S L m	70%	88%	21%	41%	4%	73%
XWV5 − − + s l M	79%	88%	12%	38%	0%	84%
XWV6 + − + S l M	77%	75%	12%	41%	0%	77%
XWV7 − + + s L M	72%	86%	16%	31%	2%	70%
XWV8 + + + S L M	80%	97%	13%	24%	0%	88%

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Vita

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